Towards Safe Robot-Human Collaboration Systems using Human Pose Detection*

Christopher Reardon, Huan Tan, Balajee Kannan, and Lynn DeRose

Abstract— **This paper proposes a human detection-based cognitive system for robots to work in human-existing environment and keep the safety of humans. An integrated system is implemented with perception, recognition, reasoning, decision-making, and action. Without using any traditional safety cages, a vision-based detection system is implemented for robots to monitor the environment and to detect humans. Subsequently, reasoning and decision making enables robots to evaluate the current safety-related situation for humans and provide corresponding safety signals. The decision making is based on maximizing the productivity of the robot in the manipulation process and keep the safety of humans in the environment. The system is implemented with a Baxter humanoid robot and a PowerBot mobile robot. Practical experiments and simulation experiments are carried out to validate our design.**

I. INTRODUCTION

Safety in human-robot collaboration and human-robot co-existing environment is of highest priority. Safety concepts are defined following the famous Three Laws of Robotics [1]:

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

From these laws, it is expected and required that robots working in human-existing environment operate safely and provide any signals related to safety issues to humans. On one side, from social science prospective, safety rules should be enforced to enable robots to make suitable and correct decisions when they have to deal with complex task-relevant situations; on the other side, from the engineering perspective, balance between productivity and safety should be well-maintained to achieve desired system performance. There is no defying the fact that under no circumstances, robots could sacrifice safety requirements to achieve unsafe productivity. Mathematically, this is a typical constrained optimization model of hierarchy description with different levels of priorities. The setting of these priorities is totally based on the Three Laws of Robotics.

However, different technologies incorporated into a safety system could affect the overall system performance. For example, different processing time impacts the synchronization or system components, especially in a distributed system design. Thus, integrated planning and coordination should be taken into consideration to achieve goals and objectives on all the layers and sub-groups of the overall system.

In this paper, we apply our safety concepts in a practical system which requires the collaboration between robots and humans and maintains the safety of humans in the working environment. This system is implemented as a part of an automated system in hospitals.

The rest of this paper is organized as follows: Section II introduces the motivation of the safety concept in a large system; Section III explains the system design; Section IV evaluates the system using experimental results; and Section V summaries this paper and proposes the future work.

II. MOTIVATION

Applying robots in the healthcare domain is attractive and challenging, especially for handling surgical tools. In a Veteran Affairs (VA) hospital, thousands of surgical tools are transported between Operating Room (OR) and sterilization room every day for surgeries and for sterilization. In most hospitals today, tools are counted by hand. This process is inefficient and could lead to critical delays in accounting for and locating surgical instruments. According to the Institute of Medicine, between 44,000 and 98,000 patients die every year due to preventable medical errors accounting for a $12-$25 billion cost to the U.S healthcare system [2].

As shown in Fig.1, a fully automated robotic application should involve several robots for both manipulation and transportation. Automating the device recognition, delivery, and accounting processes could significantly reduce costs. It is reasonable to deploy robots in such working environments to automate the process of transportation and sterilization and keep our doctors and nurses from daily repetitive and harmful process. However, safety issues arise in situations where autonomous robots must work alongside humans.

A traditional method is to put safety fence or cages around robots. Some international standards enforce strict requirements on safety [4] [5] [6]. However, following this type of solution, the mobility and ability of mobile robots could be significantly limited. Moreover, when humans have to interact with robots and thus work inside the "cage", the traditional method cannot address the safety problem.

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Reardon performed the work when he was with GE Global Research (e-mail: creardon@utk.edu).

Tan, Kannan, and DeRose are with the Software Science and Analytics, GE Global Research, Niskayuna, NY 12309, USA (email: huantan@ieee.org).

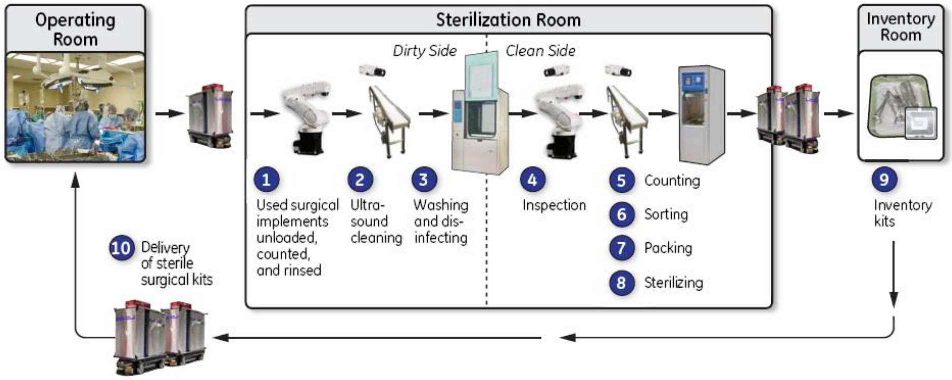

Figure 1. Overall Project Architecture

Some researchers try to develop innovative mechanisms to provide safety function for applications [6] [7] [8]. However, in our project, we do not want to manufacture a robot, which means we cannot modify the robot at will.

There is growing interest in developing collaborative robots such as Baxter robot from the Rethink Robotics company [9] and UR series robots from Universal Robots company [10]. These types of robots aim at adjusting manipulator motions to adapt to external forces, especially the interactive forces between robots and humans [11] [12]. Collaborative robotics is very promising, but it is still in its early stage. Moreover, we have not been able to find a mobile collaborative robot that meets the needs of our projects.

In our system, two robots are used to demonstrate the application of our safety concepts. One humanoid robot, Baxter robot, is equipped with a Kinect Sensor and responsible for performing routine work and monitoring the overall environment especially the location of humans and robots. The other mobile robot moves around in the environment without actively searching any human activities in the environment. The Baxter robot is able to detect environmental information, realize what the current situation is, and make decisions to generate corresponding actions. Although it cannot control the mobile robot directly, the Baxter robot is able to send out warning signals to humans.

The motivation of this paper is to develop an integrated system to enable one robot to monitor the whole working environment using Kinect sensor, make decisions based on pre-defined criterions, and send out corresponding signals. Safety modules are placed on robots to ensure robots do not hit any humans in the environment. However, there is a compelling need to augment the system's safety in cases where a human actively creates an unsafe operating situation, e.g., walk to a robot or block a robot. Sometimes, there are several humans in the environment. The human, whose distance between him/herself and the robots are the smallest, are considered as primary source information for decision making.

III. METHODOLOGY

As stated in the last section, our developed system should enable a robot to simultaneously perform multiple tasks including planning and execution, and to guarantee the human safety in the working environment. In order to achieve this goal, we must consider the integration of the perception, recognition, reasoning, decision-making, and action issues at the same time.

The implementation of the overall system is displayed using a block diagram as shown in Fig.2.

The overall system architecture could be divided into four major parts: *Perception*, *Reasoning*, *Decision Making*, and *Action*. Components in the Perception part fetch the information from the environment using a Kinect sensor [13], and from the robot using Encoders and Force Feedback Sensors. Based upon the collected sensory information, robots are able to recognize the current activity of a detected human. Recognized results and environmental information is sent to the *Evaluation* in the *Reasoning* part for further processing. The *Evaluation* block determines the current task and makes decisions to select actions based on the current robotic, human and environmental information. Selection is based on balancing the productivity of the manipulation task and the safety requirements. The interfacing between the user application and the actuators, sensors, etc. on the Baxter robot is through the Baxter Research SDK.

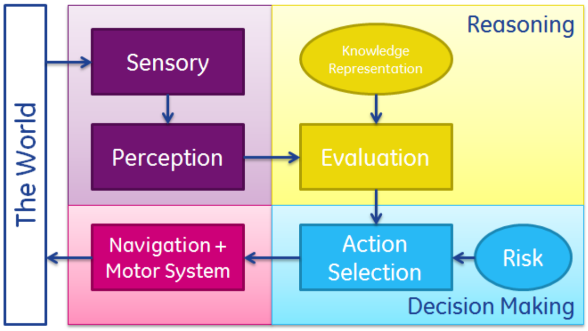

Figure 2. System Architecture

A. *Perception*

Perceptual information is used for Sensory-Motor Coordination and higher level processing. Perception includes not only obtaining the images, audio, and other sensory data from the environment, but also extracting useful information from them.

In our system, two types of sensors are used for Perception: Kinect sensor mounted on the robot head for tracking human activities in the environment; encoder and force feedback sensors on the joints of robot arms and grippers for obtaining information from the robot.

The Kinect sensor can track up to six people in the environment. After initialization, the Kinect sensor runs in a continuous loop of tracking and records positions of the people in a 6×20 array.

$$P_{people} = \{P1, P2, P3, P4, P5, P6\}^T \qquad (1)$$

where each element $P_i (1 \le i \le 6)$ is a 20×1 row vector which stores the positions of 20 joints of a human skeleton. If the number of tracked people is smaller than 6, the rest of the array will set to null.

The information mentioned above is organized in ROS message format and published on ROS topics for the recognition and reasoning modules to use. The information sent to an observation model is the positions of humans. In order to reduce processing time of our algorithm, we simply use the positions of human heads.

B. *Recognition*

Human activities in the working environment are task-related, which means that it is possible to predict human activities based on the current status of humans and environmental information. In our system, we are more interested in the position of human bodies in the environment. Thus, we choose position of humans as the main observation feature as the main input of the recognition model.

In Fig.3, a working environment is described with five work-benches (WB) and five working locations (WL). Each working location is related to a corresponding state in the observation model.

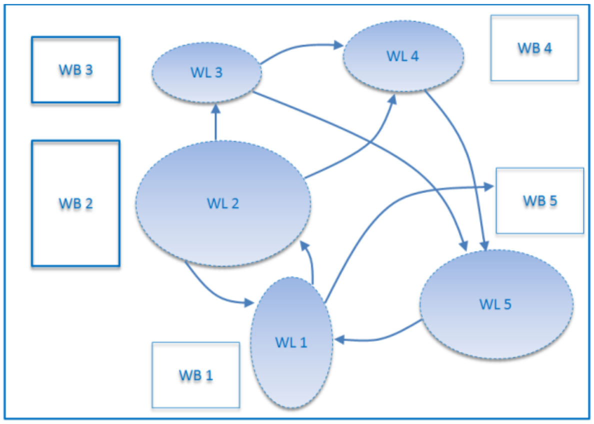

Figure 3. Working Environment

The transition probabilities between states are represented as:

$$a_{ij} = P(q_{t+1} = S_j | q_t = S_i), 1 \le i, j \le N \qquad (2)$$

The transitions are determined by some predefined operation processes.

For each state, the Baxter robot uses the Kinect sensor to detect the location of the humans. However, because of the existence of the measurement error in devices, the disturbance in the environment, or even the wrong operations of the operators, the measured information is considered probabilistic.

Then, the observation probability is given by:

$$b_{ik} = P(v_k | q_t = S_i), 1 \le i \le N, 1 \le k \le M \qquad (3)$$

It means that the measured value is v_k at time t while the current state is S_i.

Using the observation result, we can obtain the belief of which state the human is in, which follows a Gaussian distribution.

The state with highest probability will be chosen and sent to *Reasoning and Decision Making* module for further processing.

C. *Reasoning and Decision-Making*

After the task is started, two tasks are running simultaneously: the Manipulation and the Safety. This multi-task execution architecture highlights the importance of safety to provide a safe environment for human and robots in VA hospitals. The Reasoning part receives the messages from the recognition part. Using the environmental information and the pre-defined knowledge, an Evaluation mechanism can make decisions and select actions based on the current task-relevant situation.

Fig.4 displays the general Mechanism. An important issue in decision making is to maximize the productivity while keeping the safety of humans. We do not want to interrupt normal routine work when humans are not in dangerous areas. Otherwise, robots can simply stop working all time when humans are detected.

Fig.5 displays a well-accepted state transition machine for the Manipulation task. In each operation, the Baxter robot reaches the tool to be manipulated, uses a gripper to pick it up, and drops it in a desired tray.

Fig.6 displays the safety task implemented in our system.

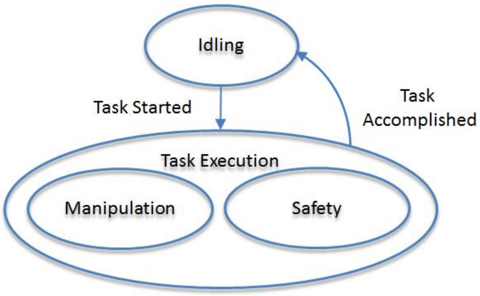

Figure 4. Overall System Work Flow

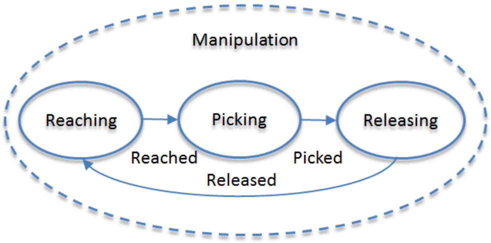

Figure 5. Manipulation Task

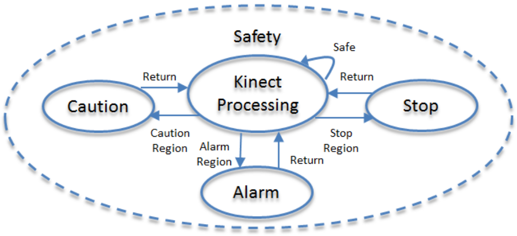

Figure 6. Safety Task

Depending on the recognition results of using Kinect information, the Baxter robot recognizes the current location of the human and predicts the future location of the human after a pre-defined timing window. Based on the recognized and predicted results, the Baxter robot may quickly make a decision to switch states in the safety task. If a human is detected and far away from the mobile robots in the environment, the robot keeps an eye on the human; if the human's proximity to a mobile robot is becoming a concern, the Baxter robot sends out alarm signals; if the robot predicts that the human is moving too close to a mobile robot, and a collision is inevitable unless either the mobile robots or the human stop their current activity, it performs a STOP signal to the human.

However, in practical applications, simple rules are enough. A very interesting and important problem is to handle the balance between productivity and safety.

In our definition, productivity refers to normal operations in the process without any interruption or exception. Productivity directly contributes to the system performance especially the normal operation performance. In our design, we would like to maximize productivity which means we do not want to unnecessarily interrupt normal operations.

On the other side, the safety of human operators and other robot agents in this system is the highest priority. Any injury or damage should be avoided.

In order to handle the balance between productivity and safety, we used a weighted function to describe the overall award from the decisions.

A policy with immediate rewards is described as shown in equation (4):

$$Q_\pi(s,a) = E\{r_{t+1} | S_t = s, a_t = a, \pi\} \tag{4}$$

where s is the state, r is the reward, a is an action, π is a policy, and t is timing step.

The award is computed as:

$$r_{t+1} = e^{d-d_0} * P + e^{-\|d-d_0\|} * S \tag{5}$$

P means productivity actions, and S means safety actions. The value 1 for two variables means the robot decides to take the corresponding action, and 0 means no action is made. P and S cannot be equal to the same value at the same time.

In our design, safety task is of the highest priority and can override any manipulation tasks when required. This decision is made by maximizing the computing result from equation (5).

Intuitively, when the distance between the robot and the human is smaller than a predefined value d_0, the second term of equation (5) becomes negatively large. Then we need to take action $(S = 1)$ to maximize r_{t+1}. If the distance is larger than d_0, the second term is also very small, then $(S = 0)$.

D. *Action*

The Motion Planning plans all the motion trajectories for the states to perform tasks. These motion trajectories are as a sequence of data points to the Baxter Research SDK to move the arm to the desired position through these waypoints with specified orientation. We manually teach the Baxter robot to execute certain motions to send out alarm signals.

Additionally, Fig.7 displays the face images developed for the Baxter robot for the safety task. When the human is in different regions around the mobile robot, the Baxter robot will display different face images.

Figure 7. Face Images

Using the positions of tracked people in the environment and the pre-defined regions for different levels of safety, the decision-making module can trigger the Safety task to send out corresponding alarm signals. Related to the face images in Fig.7, the Baxter robot will lift the right arm when the human is in danger area and two arms when it is required to send out STOP signal.

Four safety regions are used in our system including Safe, Caution, Danger, and Emergency Stop. These regions are related to the distance between the human and the robot from the farthest to the nearest respectively.

The content on the LCD screen is changed (the head of the Baxter robot) to display different safety signals related to current situation. Fig.7 displays the images we used in our system.

In order to realize such a multi-task execution system, Besides the Baxter Research SDK and the nodes related to the hardware sensors, each task is implemented as an independent ROS node. All the nodes share the information published on ROS topics.

IV. EXPERIMENTAL DESIGN AND RESULTS

Normally, two criteria are used to evaluate system performance on safety issues: 1. Success rate; 2. Response time.

Fig.8 displays the experimental scenario. When robots, including the PowerBot and the Baxter robot, are working, a human enters the environment. The human will work in the environment together with PowerBot and Baxter robot. The location of the human is not static, since he/she works at different working locations and the motion happens from time to time. The objective of our experiment is to guarantee the safety of the human, which requires the Baxter robot send out corresponding alarm signals while the human works at different locations which are tightly related to different safety situations.

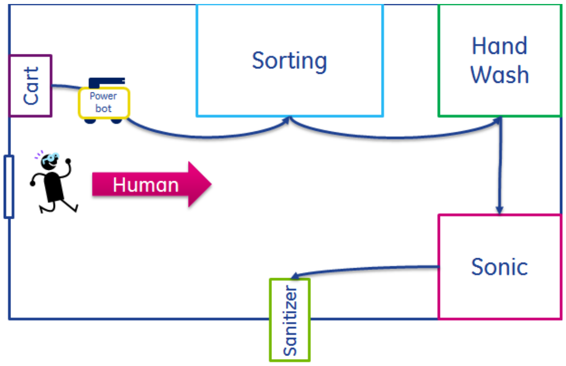

Figure 8. Experimental Scenario

Since this is a system integration level implementation, we only test the functional performance of our developed system. The quantitative results largely rely on different pieces in the system.

Fig.9 displays the experimental setup in this paper. The Baxter robot monitors the environment using the Kinect sensor on its head. For this experiment, the PowerBot is operating in a fixed position.

Fig.10 displays the safety areas around PowerBot computed using equation (5).

Fig.11 displays a typical example of the responses from the Baxter robot when the human is already or is predicted to be in different safety areas. From the experimental results, we can see that the Baxter robot can correctly distinguishes the current situation of the human in the environment, displays corresponding image on the screen, and uses its arms to send out corresponding signals.

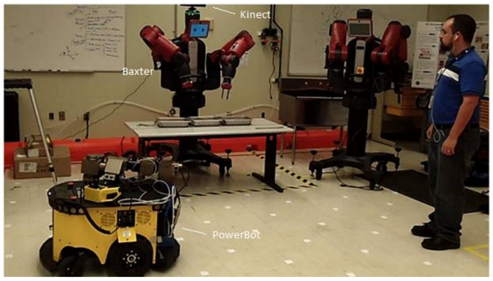

Figure 9. Experimental Setup

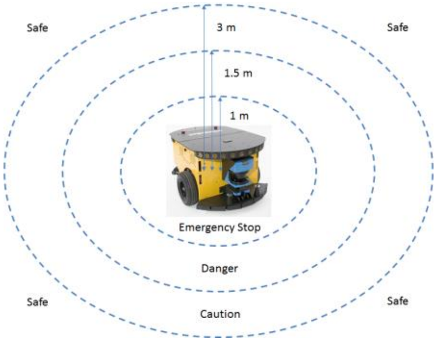

Figure 10. Safety Areas

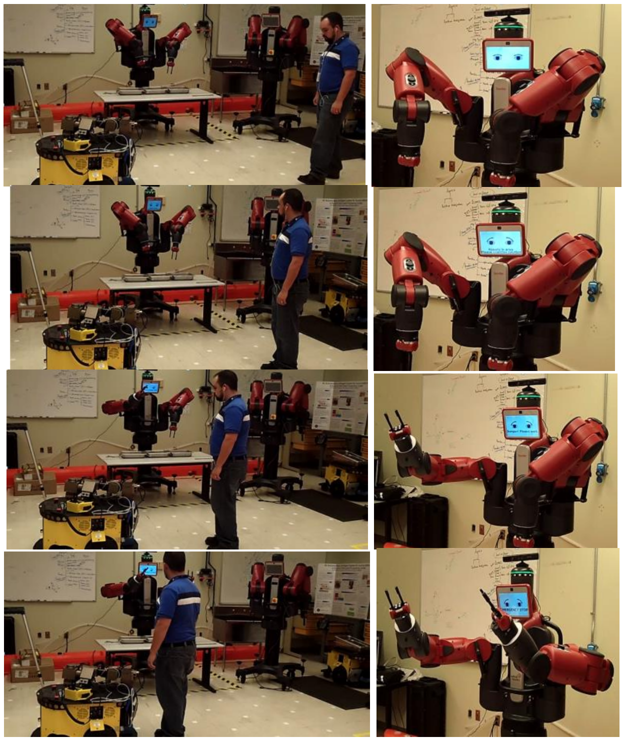

Figure 11. Experimental Results

The response time depends on the processing time of the Kinect sensor and the response rate of the SDK. The frame rate for Kinect sensor is related to the resolution of the images. The fastest rate is 30Hz. The control rate of the head is 1Hz. The control rate of the joint is also around 1Hz. That means, if we use the head and the arm to send out the safety signals, the response time is around 1100 ms. However, if we use other methods, for example, sound, it can largely reduce the response time to 50~70ms. No matter what method we use, the response time is satisfactory unless somebody purposely runs very fast in the working room.

V. CONCLUSION

This paper proposes an integrated system for human-robot collaboration or human-robot collaborative environment. The system is implemented using perception, recognition, reasoning, decision-making, and action. A vision-based sensory component is used for Baxter robot to monitor the environment, and provide safety signals for humans. Experimental results demonstrate our system is effective to deal with practical task-relevant applications. In our experiments, we use a mobile robot operating at a stationary position. In the future, we will construct a dynamic environment with several mobile robots running. In such case, the reasoning and decision making process will be more complex, which requires using a sensory information fusion method to handle such a complex case and to conquer the timing lag in the system. In this paper, we only implemented a simple human detection-based system. However, this method is not very robust since the estimation of human poses is not accurate. In the future, we plan to incorporate human-gesture recognition in our system. Gesture recognition results could provide much more information for robots to analyze and predict human activities in the environment.

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