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Risked-based Design for the Physical Human-Robot Interaction (pHRI): an Overview

Fahimeh Rezazadegan*[a], Jie Geng[b], Marco Ghirardi [a], Giuseppe Menga [a], Salvina Murè[b], Gianfranco Camuncoli[b], Micaela Demichela[c]

[a] Dipartimento di Automatica e Informatica, Politecnico di Torino, Corso Duca degli Abruzzi, 24 – 10129 Torino, Italia
[b] ARIA s.r.l. – Corso Mediterraneo 140 -10129 Torino, Italia
[c] SAfeR, Dipartimento di Scienza Applicata e Tecnologia, Politecnico di Torino, Corso Duca degli Abruzzi, 24 – 10129 Torino, Italia
fahimeh.rezazadegan@polito.it

Collaboration and sharing workspace between human and robots has turned into a challenge that has to be taken into account in many industrial domains, including the process industry. In this study, literature related to risk-based safety system design is reviewed as well as relevant research of control design for safety issues. The paper mainly presents two key contributions. 1) planning for safety: risk-based safety analysis methodologies are reviewed to analyze current methods for identifying the potential risks caused by abnormal operation and failures in the human-robot interaction environment. The risk assessment methodologies are including not only functional risk analysis, but also human reliability analysis. The results from risk evaluation will help making HRI safety strategies which are series decision makings to support the further engineering design of a pHRI safety system. 2) Control design system for achieving safety: to reach a comprehensive safety system design and limit accidents in the human-robot interaction environment, four scenarios are taken into consideration: proximity detection, collision avoidance, docking and compliance control. Current control techniques in each domain to guarantee the safety of system are reviewed. Finally, most common used methods in the above-mentioned areas are introduced and their performance is discussed.

1. Introduction

Today, one of the most prominent milestones luring the robotic community is the integration of a robot's and a human's workspace (Santis, 2008). Considering the increasing robot use in all fields from industrial factories to medical environments and a wide variety of its applications in close vicinity of human, the need of a safe comprehensive control design that can overcome all difficulties in human-robot interaction domain and guarantee the safety of human using risk reduction strategies, is required for cooperative tasks between human and robot in common workspace.

In Pervez &Ryu (2008)'s review works, the classification of robots based on their application modes can be divided into cooperation, assistance, teleoperation and entertainment, etc. This overview mainly considers the cooperation mode. Especially, according to a report from PHRIENDS 6th FP EU project (Santis, 2008),human-robot interaction will certainly happen at both of the cognitive Human-Robot Interaction (cHRI) and physical Human-Robot Interaction (pHRI). The cHRI fundamentally concerns mental models and communication between human and robot; and the pHRI concerns the scenario that humans and robots share the same workspace, come in touch with each other, exchange force, and cooperate in doing actions on the environment. This study is only involving physical Human-Robot Interaction (pHRI). The main requirement of pHRI is to guarantee the safety of non-professional people who are using or are present around the robot.

The safety of human through the sharing of a robot's workspace has been the purpose of this research. The work was carried out on different fronts which can be described under headings of risk-based HRI safety planning, HRI Safety strategies and HRI safety control system. The concept of risk assessment, which is more

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common used in industrial environment, is included in relevant robot standards to guarantee safety by defining an area where the robot stops when detecting human is approaching (Macfarlane & Croft, 2003). In this study, risk-based pHRI safety system design concept is proposed, and relevant safety assessment methodologies are reviewed. It helps pHRI safety system designer to make safety strategies for the further control system design through four scenarios: proximity detection, collision avoidance, docking and compliance control.

2. Framework of the study

Risk-based pHRI Safety System Design is a design method that is a risk based, through HRI safety risk assessment on both of robots and humans' reliability, to provide the potential hazard identification, risk analysis and risk evaluation results for the HRI safety strategies design. HRI safety strategies are a series of decisions with considering which type of safety components should be applied in different identified risky scenarios, e.g. monitoring techniques, prevention or protection techniques.

In a control system design the proximity detection is one of the first section that should be taken into consideration, because if a human presence in a workspace can be detected by the robot, suitable control strategies could be implemented. As far as preventing a contact occurrence is the objective, an effective collision avoidance method should be performed. If a cooperative task between human and robot is aimed, designers need to find an optimal solution for docking and compliance control. Strategy of docking tries to reach contact position with zero velocity, while the compliance control has to be implemented in order to keep the force exchanged between human and robot, under desired bounds. As a result, the framework of a pHRI safety system design can be assumed as in figure. 1.

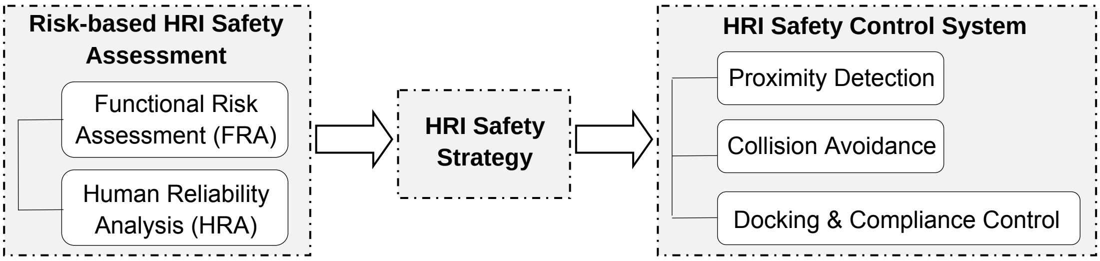

Figure.1. Framework of pHRI Safe System Design

3. Overview of risk-based HRI safety assessment

In the early robot design phase, planning for safety coupled with the potential HRI hazard identification has received less attention than control techniques. However, safe planning is important as a means of reducing potential hazards by covering safety criteria and can improve the control outcome.

Functional Risk Assessment (FRA): In order to deal with the further robot functional risk assessment, some classical risk assessment methodologies are presented. Those methodologies are categorized into three groups (Marhavilas et. al, 2011; &ISO/IEC 31010, 2009):

1) Qualitative Risk Assessment Techniques, like Checklists, Preliminary Hazard Analysis (PHA), What-if Analysis, Sequentially Timed Event Plotting (STEP) Technique, Hazard and Operability Study (HAZOP), Failure Mode and Effects Analysis (FMEA).

2) The classical Quantitative Risk Assessment Techniques are: Proportional Risk Assessment Technique (PRAT), F-N Curve, Domino Scenarios (QADS), Weighted Risk Analysis (WRA).

3) Moreover, hybrid techniques combine advantages both of qualitative techniques and quantitative techniques and are more reliable that can be used in the real practical environment, such as Event Tree Analysis (ETA) and Fault Tree Analysis (FTA).

Human Reliability Analysis (HRA): Many risk assessment techniques are mainly concerning machine functional failure itself, however, nowadays, more and more safety managers and researchers realize that the system of mechanical industry is a complex human-machine system, which is composed of humans, machines, and the interaction between them. Evans (1976) explained that human reliability is a probability that a person correctly performs some system-required activities in a required time period, and performs no extraneous activity that can degrade the system. Human Reliability Analysis (HRA) is a method for the estimation of human reliability. Some classical HRA techniques are: Technique for Human Error Rate

Prediction (THERP) proposed by Swain & Guttmann (1983), Cognitive Reliability and Error Analysis Method (CREAM) proposed by Hollnagel(1998), Human Error Assessment and Reduction Technique (HEART), A Technique for Human Event Analysis (ATHEANA), etc.

Current Risk Assessment Application in pHRI: Among these current risk assessment techniques, some of them are already applied in pHRI environment.1) HRI Safety Index: the most common use are Gadd Severity Index (GSI) and Head Injury Criterion (HIC).2) UML-based HAZOP Analysis was proposed by Guillerez et al. (2010). UML, Unified Modeling Language is used to describe the HRI as the system description. HAZOP risk analysis method is used for the risk analysis. 3) Risk Management Simulator: Ogure et al. (2009) proposed for low-powered human-collaborative industrial robots, and is considering pHRI scenario. The risk management simulator is based on CHAT (Coexistence Hazard-Avoidance Technology). The potential pHRI hazard identification uses Preliminary Hazard Analysis (PHA) method.4) Fuzzy-based Risk Assessment: Ogorodnikova (2009) proposed an extended approach for the risk assessment and reduction Algorithms. The risk assessment algorithm is a part of the Expert System's (ES) interference engine. After the information is given in input to the ES graphical interface, fuzzy logic is applied for the precise probabilistic or mathematical analysis.

4. Overview of HRI safety strategies

There are some researchers divided pHRI safety strategies into two directions: passive safety strategy mainly focuses on designing robot with reducing the collision forces during the special emergency scenario; active safety strategy mainly focuses on preventing pHRI collision at the control level. Some pHRI safety strategies are reviewed as bellowing:

Pedestrian Behavior Prediction Safety Strategy: It is pre-collision safety strategy developed by Tamura et al. (2013).

Pre-collision HRI safety strategy: Kulić and Croft (2007) proposed a pre-collision safety strategy with three components for dealing with safety at different time horizons of Safe Planning (long term safety), Trajectory Scaling (medium term safety) and Reactive Control (short term safety).

Learning-based safety control strategy: Calinon, et al. (2010) proposed a control strategy for a robotic manipulator operating in an unstructured pHRI environment.

Withdrawal strategy for human safety: The purpose of withdrawal strategy is to increase the distance between human and robot when they are getting too closer. Virtual force model is applied to modify the end-effector velocity and move it not only away from the human but also towards a parking position (Ricardez et. al, 2013).

Constraint-based strategy for task-consistent safe HRI: Ceriani et al. (2013) defined a method for designing task-consistent collision avoidance strategies, in order to productively combine task execution and safety actions in the industrial HRI environment.

5. Overview of HRI control system

In the physical human-robot interaction field, the most frequently used control strategy might be impedance control and its variants, though other methods also exist. Since robots are controlled to move relatively slowly when interacting with people, the impact velocity is decreased in accidents. Many surveys addressed the control in a safety issues such as Formica et al. 2006, Kikuuwe and Fujimoto 2006.

Proximity detection: Usually, the common solution in industrial robotics was to employ proximity sensors such as laser beams to figure out the presence of a human worker in a vicinity of the robot, and then stop the task execution. To cope with this conservative approach, and to allow the interaction between humans and robots, active collision avoidance policies have been advocated. Theses approached are based on 1) real-time detection and localization of human workers in the robot ambient, and 2) reactive planning algorithms to avoid collision. Detection and localization have been addressed by employing different sensing techniques.
Najmaei and Kermani (2011) introduced a new sensory system for modeling, tracking, and predicting human motions within a robot workspace. In addition, self-organizing maps (SOMs), is used for obtaining a super quadric-based model of the human in which the SOM network receives information of the human's footprints from the sensory system and infers necessary data for rendering the human model. Since this paper used

ANN, a large number of inputs for increasing accuracy was unavoidable that resulted in having computational complexity and also a great deal of time that can be a drawback of this method.

Collision avoidance: Collision safety in pHRI is an attractive broad area of research and several promising methods have already been proposed in the previous work. Collision safety through planning and control is the most common-used method to guarantee human safety where control strategies are implemented for avoiding the accident. Primary methods in robot navigation on the basis of artificial potential fields and virtual forces (Khatib 1986, Borenstein and Koren 1991) have some limitations that make it be inapplicable for real robots.

One of the famous methods for collision avoidance that can be simply found among the previous research is the velocity obstacle method that is introduced by Fiorini and Shiller 1993 at first. In this technique, a velocity set in the velocity space is employed for determining the future collisions regarding with the relative velocity rather than other agents. Papers using this approach usually consider the case of holonome robot and linear constant motion of the obstacles that can be a disadvantage and should be generalised.

Another common used approach in the area of collision avoidance is dynamic window approach that is proposed by Fox et. al. 1997 for the first time and then it is developed by another researchers (Kiss and Tevesz 2012, Saranrittichai et al. 2013). The approach is derived directly from the motion dynamics of the robot and incorporates the dynamics of robots by reducing the search space to the dynamic window, in which there are only admissible velocities reachable within a short time interval. Then, the velocity optimizes the objective function that is a weighted sum of three terms of the heading direction of the robot, the distance to the obstacle and the velocity of the robot. It should be mentioned that this approach only assumes geometric information about the relative location of obstacles and is suitable for sensors like ultrasonic transducers or laser range-finders.

Docking: Undoubtedly, one of the most necessary capabilities for mobile robots with the aim of having interaction with objects or even human in their environment is Docking. In some tasks such as transporting goods on a factory floor or performing cooperative tasks with human in which docking maneuvers are needed, it is so critical that robot's deceleration to a final stop can be done in such a way that robot can reach to the sufficient proximity of object or human to happen the interaction without any collision occurrence. Due to this purpose, time of contact should be estimated and velocity of the robot needs to be controlled.

Low and Savkin 2006, proposed a vision-based docking system to control the approaching motion of a wheeled mobile robot toward a static target using just a video camera. This idea came from insect navigation.

It should be mentioned that this method is proposed by Manchester and Savkin2005, for the first time.

The control law not only does not try to observe the relative pose of robot and target, but also only uses the prompt visual information for the control process, but relying on only visual information can be viewed as a drawback for system.

Low et al. 2007, presented a behavior-based control law is presented while the vision system is based on the concept of the active vision paradigm. Video camera is located on a wheeled robot and for making sure about maintaining the sight of an object of interest in an environment, a visual gaze algorithm based on the concept of eye–head coordination is employed.

Compliance control: One of the most key problems in the area of human and robot interaction can be the adjacency and adaptability to environment, above all in the case of moving robot in an unknown or unstructured ambient. Compliance control can be a suitable candidate for this issue. In general there is a relationship between the gain of disturbance observer that is widely used for enhancing robustness and stability in compliance control and larger DOB's cutoff frequency is leading to stabilize systems.

Compliance control is to control the position and force through virtual impedance. In fact, compliance control can reduce reaction force differently from position control. In position control, a robot can't control the reaction force if it contacts to environment. Then, the environment may be destroyed in contact motion. Therefore, compliance control is suitable to apply flexible motion control and mobile robot like electric wheelchair introduced by Katsura and Ohnishi 2004 and legged robot proposed by Wei et al. 2010, and so on.

6. Conclusion and future work

In the HRI area, visual sensing techniques are commonly used for proximity detection. In particular, Kinect sensors are highly recommended. In order to have an effective collision avoidance algorithm, the dynamic window approach seems appropriate in this area. The most important advantages of this approach can be flexibility for modifying and capability of dealing with the uncertainty. Computer vision-based docking offers the ability to use simple and more general docking stations (simple visual patterns). Additionally, computer vision is a compact and low cost sensor popular in general robot control literature. Among all literature review been carried out, he most common used control method in the compliance field can be impedance control. Accordingly, control system design can be considered as figure. 2. The coexistence of humans in robots' operational domains brings a significant risk of dangerous situations for those involved. Hence, surveys in the area of human robot cooperation requires to be considered from the safety and risk assessment points of view as well as system control prospective. Although, all above mentioned approaches can be useful in keeping human robot interaction safe, their insufficient information of human bio-mechanics about the power of the human body weaken their efficiency.

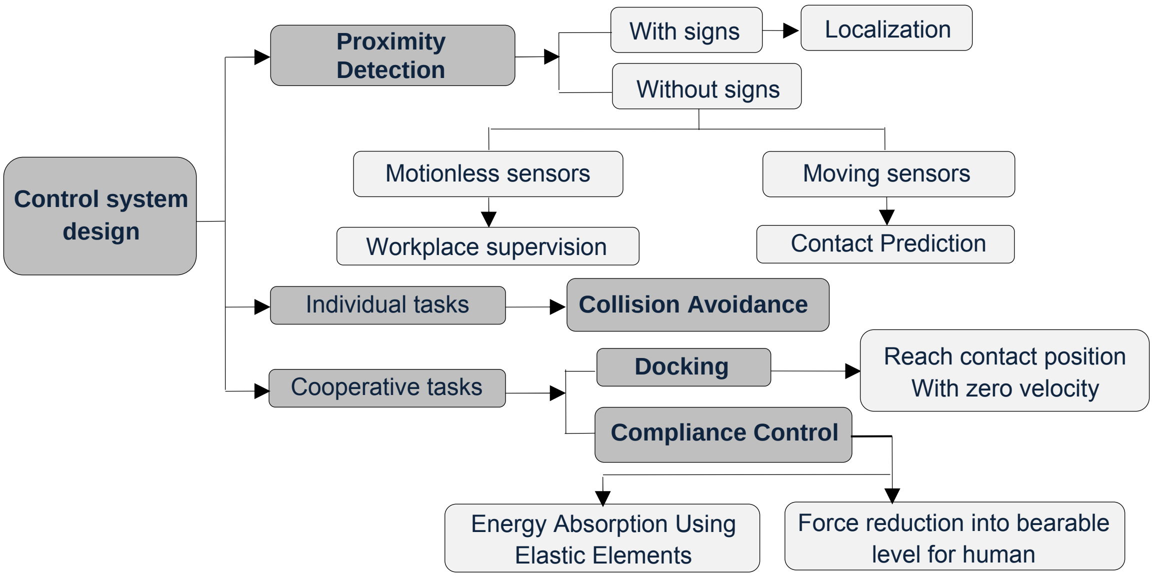

Figure 2. Block diagram of safety system designing

As a result, it is required that the study of human bio-mechanics to be more investigated in details. In this way, the robot behavior can be correlated with the estimation of injury severity under direct physical contact with the robot. For the effective risk assessment, all critical hazardous situations during human-robot interaction should be evaluated. Possible solutions to eliminate them and decrease the probability of occurrence and severity of the consequences should be found.

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References

Borenstein J., Koren Y., 1991, The vector field histogram - fast obstacle avoidance for mobile robots, IEEE Trans. Robot. Autom., vol. 7, 278–288.

Kulić, D. & Croft, E. A., 2006, Real-time safety for human-robot interaction. Robotics and Autonomous Systems, vol. 54, 1-12.

Calinon, S., Sardellitti, I., & Caldwell, D. G., 2010, Learning-based control strategy for safe human-robot interaction exploiting task and robot redundancies, The 2010 IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems, October 18-22, Taipei, Taiwan.

Ceriani, N. M., Zanchettin, A. M., Rocco, P., Stolt, A., Robertsson, A., 2013, A constraint-based strategy for task-consistent safe human-robot interaction, 2013 IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems (IROS), November 3-7, Tokyo, Japan.

De Santis A., Siciliano B., De Luca A., Bicchi A., 2008, An atlas of humrobot interaction,Mech. Mach. Theory, vol. 43, 253–270.

De Santis, A., 2008, Modelling and control for Human-Robot Interaction: physical and cognitive aspects, 2008 IEEE International Conference on Robotics and Automation, Retrieved from PHRIENDS website: http://www.phriends.eu/papers.htm

Evans. R. A., 1976, Reliability Optimization, In E. J. Henley & J. W. Lynn (Eds), Generic Techniques in Systems Reliability Assessment (pp. 117-131). Leyden, Netherlands: Noordhoff International Publishing.

FioriniP. and Shiller Z., 1993, Motion Planning in Dynamic Environments Using the Relative Velocity Paradigm, *Pmc.* IEEE *Inr. Con$ Robotics Automat.,*Vol. 1, 560-565.

Formica D., Zollo L., Guglielmelli E., 2006, Torque-Dependent Compliance Control in the Joint Space for Robot-Mediated Motor Therapy, Journal of Dynamic Systems, Measurement, and Control, vol. 128, 152–158.

Fox D., Burgard W. and Thrun S., 1997, The Dynamic Window Approach to Collision Avoidance, IEEERobotics and Automation Magazine, vol. 4, 23-33.

Guillerez, D. M., Guiochet, J., Powell, D. & Zanon, C., 2010, Retrieved from http://sed.bordeaux.inria.fr/people/damienmartinguillerez/publi/conf/2010-SERENE.pdf

Hollnagel, E., 1998, Cognitive Reliability and Error Analysis Method: CREAM. Oxford: Elsevier Science Ltd.

ISO/IEC 31010, 2009, Risk management — Risk assessment techniques.

Katsura, S. , Ohnishi, K., 2004, Human cooperative wheelchair for haptic interaction based on dual compliance control, IEEE Transactions on Industrial Electronics, vol. 51, No. 1,221–228.

Khatib O., 1986, Real-time obstacle avoidance for robot manipulator and mobile robots, The International Journal of Robotics Research, vol. 5, 90–98.

Kikuuwe R., Fujimoto H., 2006, Proxy-based sliding mode control for accurate and safe position control, Proceedings of the 2006 IEEE International Conference on Robotics and Automation, 25–30.

Kiss D., Tevesz G., 2012, Advanced dynamic window based navigation approach using model predictive control, 17th International Conference on Methods and Models in Automation and Robotics (MMAR), 148 – 153.

Low, E.M.P., Savkin, A.V., 2006, A method for vision-based docking of wheeled mobile robots, IEEE International Conference on Control Applications,Computer Aided Control System Design, 614-619.

Low E.M.P, Manchester I.R., Savkin A.V., 2007, A biologically inspired method for vision-based docking of wheeled mobile robots, Robotics and Autonomous Systems, Elsevier Journal, Vol. 55, 769–784.

Macfarlane, S. & Croft, E., 2003, Jerk-Bounded Robot trajectory planning-Design for real-time application. IEEE Transactions on Robotics and Automation, 19(1):42-52.

Manchester I.R., Savkin A.V., 2005, Vision-based docking for biomimetic wheeled robots, Proceedings of the 15th IFAC World Congress, Prague, vol. 16, 2051-2051.

Marhavilas, P. K., &Koulouriotis, D. E., 2008, A risk estimation methodological framework using quantitative assessment techniques and real accidents' data: application in an aluminum extrusion industry, Journal of Loss Prevention in the Process Industries, 21(6), 596-603. doi:10.1016/j.jlp.2008.04.009.

Najmaei, N., Lele, S., Kermani, M. R., &Sobot, R., 2010,Human Factors for Robot Safety Assessment, 2010 IEEE/ASME Intl. Conf. on Advanced Intelligent Mechatronics Montreal, Canada.

Ogorodnikova, O., 2009, A Fuzzy Theory in the Risk Assessment and Reduction Algorithms for a Human Centered Robotics, 18th IEEE International Symposium on Robot and Human Interactive Communication, Toyama, Japan.

Ogure, T., Nakabo, Y., Jeong, S. H., & Yamada, Y., 2009, Risk Management Simulator for Low-powered Human-collaborative Industrial Robots, 2009 IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems, St. Louis, US.

Pervez, A. &Ryu, J., 2008, Safe physical human robot interaction-past, present and future, Journal of Mechanical Science and Technology, 22, p. 469-483.

Ricardez, G. A. G., Yamaguchi, A., Takamatsu, J., & Ogasawara, T., 2013, Withdrawal Strategy for Human Safety based on a Virtual Force Model, 2013 IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems (IROS), November 3-7, Tokyo, Japan.

Swain, A.D., & Guttmann, H.E., 1983, Handbook of Human Reliability Analysis with emphasis on Nuclear Power Plant Applications, NUREG/CE-1278. Washington, DC: US Nuclear Regulatory Commission.

Saranrittichai P., Niparnan N., Sudsang A., 2013, Robust local obstacle avoidance for mobile robot based on Dynamic Window approach, 10th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 1-4.

Tamura, Y., Terada, Y., Yamashita, A., & Asama, H., 2013,Modelling Behaviour Patterns of Pedestrians for Mobile Robot Trajectory Generation. International Journal of Advanced Robotic Systems, 10, p. 310

Wei X., Rong X., Jun W., 2010, Force/Torque-based Compliance Control for Humanoid Robot to Compensate the Landing Impact Force, First International Conference onNetworking and Distributed Computing (ICNDC), 336-340.