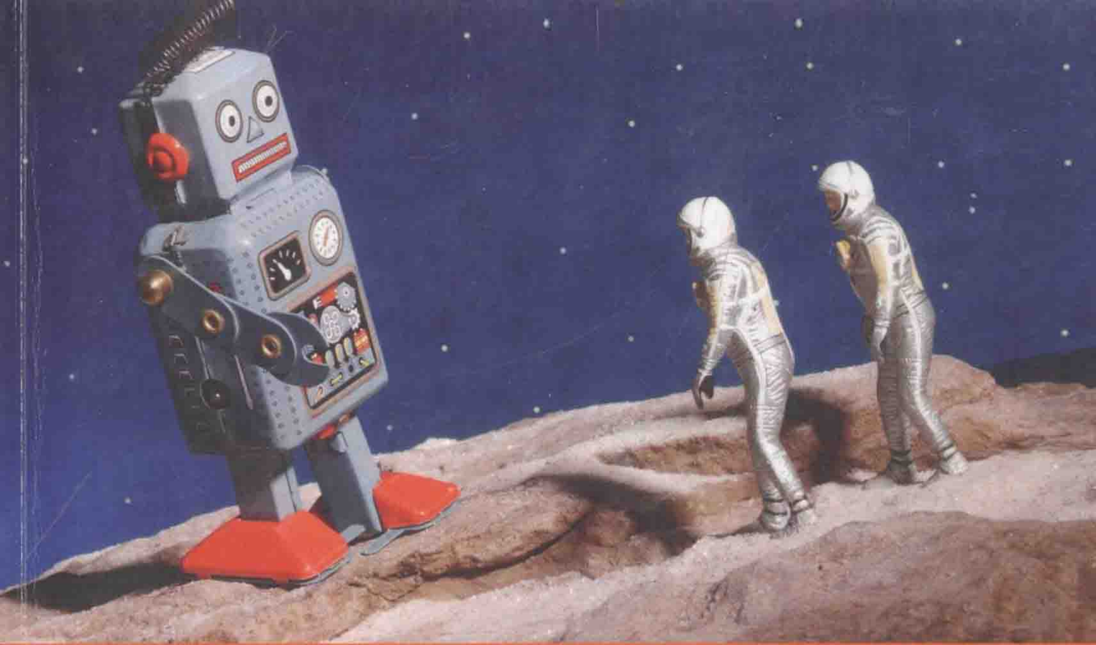

Olesya Ogorodnikova

Human-Robot Interaction: Safety Challenge

An integrated framework for human safety

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PhD dissertation

Human Robot Interaction: The Safety Challenge
(An integrated frame work for human safety)

Written by:

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Budapest 2010

Research Premise

In the past four years, my research was focused on *the Safety Challenge in Human Robot Interaction*. I have been concerned with issues of: robot's reliability, risk assessment, safety regulations and standards in advanced tasks, robot critical physical characteristics; safeguard sensory systems, ergonomics, and human factors for human-centered robotic workplace design. My research interests are concerned with both the physical and cognitive aspects of human robot interaction. In particular, the research addresses the effects of the ambient environment on human perception capabilities, human decision making mechanisms, personnel attitude toward robots especially when working in robot proximity. Driven by the need for an integrated approach to these diverse issues, my work has been aimed at the development of a framework that considers in an integrated fashion: human factors, robot characteristics, interface properties, and environment conditions. In this effort, I worked on a safety expert system that builds on conventional safety regulations to integrate newly proposed concepts for safety in advanced applications. The system is conceived to communicate with the designer by means of an interface to provide hazard analysis and risk assessment and generate the result - recommendations on how risks can be reduced within given conditions. I have also worked on the development of an active HR interface that is designed to augment human awareness about the surrounding environment, and thereby to enhance safety in human-robot coexistence and cooperation. For this purpose, I proposed a range of safety instrumentations for the human to provide him/her with active tactile and visual stimuli in the event of a hazardous situation. My recent research was focused on the integrated system development that would interconnect all earlier considered aspects, related to the human security and work convenience in the robotic operating space.

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Abstract

The safety monitoring system, developed in this thesis, is conceived to provide an integrated framework for safety by bringing together the three components of a Safety Expert System (SES), a Safety Mode Controller (SMC) and a Human Awareness Interface (HAI). The protocols of the expert system, which establish various safety criteria and functional modes, are key elements for achieving effective performance of the safety system. They are used by SMC which provides safe path modification while alerting the human through HAI about an eventual danger or any changes in the system.

The development of the expert system was meant to provide user (designer) with explicit workcell ergonomic and human factor analysis, task related hazards and risk category evaluation, which is further enhanced by means of risk reduction and safeguarding assessment methodology. The Inference Engine of the expert system, which is built on the fuzzy logic theory in combination with other techniques, provides a valuable tool for knowledge representation and processing. In its output data, the system generates a protocol that is further used for the safety mode controller operating algorithm.

A danger index has been also proposed to facilitate the collaboration at different interaction levels. Consisting of two components, this index enables to maintain a safe distance from the robot, while minimizing the probability of serious human injury in case of impact. The evaluation of the danger index is based on a human-robot collision model, where the probability and likelihood estimation of danger, human injury and pain tolerance thresholds (head), manipulator structural and dynamic characteristics (effective mass, inertia, stiffness, and velocity), and Head Injury Criteria (HIC) were all taken into account. The acquired safety criterion is integrated into the safety mode controller monitoring algorithm to determine boundary values for each safety mode associated with an interaction level.

The safety mode controller is represented as a separated unit that monitors interconnected elements (Robot, Safeguarding controllers, present sensing devices, awareness system) in compliance with safety criteria and predefined transition rules. Its functional algorithm is based on the definition of safety mode monitoring parameters and their continuous control.

A human awareness interface is a wearable device, which by means of vibrotactile and visual stimuli, intends to evoke or enhance personnel situational awareness about the ambient environment, in particular, when hazards and accidents could be encountered due to system failure or when the manipulator is exceeding its critical characteristics.

The overall safety monitoring system is an integrated safety framework that ensures the required level of safety during the performance of collaborative tasks. In the event of any failure or inconsistency, the system will respond in compliance with the predefined procedures according to the estimated level associated with the event danger, thereby reducing the severity and probability of the possible accident.

Thesis Overview

Chapter I introduces the Human Robot Interaction concept, discusses the field safety related emerging challenges and objectives. Chapter II reviews the related work in the literature on human-robot interaction from different views. In the first part, robot related hazards are specified and standard techniques for their reduction including safeguarding means with respect to each interaction level are discussed. In the next part recent, up to date strategies for estimating and improving safety at the designing, planning and control stages are considered. Chapter III is devoted to the Safety Expert System (SES) development that is devoted to enhance human safety in robotized environment. It is a computer aided advisory system which knowledge base contains requirements of some (*ANSI/RIA R15.06-1999, EN 775, ISO 10218*) existing standards in robotic safety and ergonomics, applicable for HRI domain, additional considerations related to advanced robotics associated with new areas of hazards and other knowledge required for the inference engine of the system. The inference engine of SES represents a novel approach to the task associated hazard analysis, risk assessment, work place conditions and human factors estimation. Identifying to each interaction level a risk category, the generated output provides user with the results of the analysis and recommendations on its reduction if needed. It performs a safeguard assessment with respect to evaluated risk, considering the requirements stated in robot safety standards and recent approaches in HRI realm. The expert system also integrates robot physical properties, estimating its dangerous characteristics for humans in vicinity and evaluates safety criterion for each interaction. As a result, the SES generates protocols for the safety mode authorization that subsequently is used for a SMS (safety monitoring system) operating algorithm. Chapter IV is devoted to the novel injury scale for the human robot interaction field development and to the danger criterion (DI) formalization. The introduced Danger Index consists of three main components (related to distance, force and acceleration), which impose constrains on robot operating characteristics within the interactions in human vicinity. The concept is built on a human robot collision modeling and presented in two forms: based on Newton low and Head Injury Criteria (HIC) approach. Danger index control strategies were proposed and modeled for 2 and 6 DOF manipulators. Chapter V discusses the need for a safety monitoring system to be interconnected with the robot controller and safeguarding system. This approach brings protocols form the SES for each robot task into a monitoring algorithm. In real-time operations, the system assesses the robot controller's inputs (desired task), and makes a decision whether the operation is safe for a human. Through continuous monitoring of the robot characteristics, safeguarding controller state, and monitoring system's commands, any dangerous situation is identified and appropriate response is provided in time. The safety mode controller (SMC), integrated into the safety system, also activates the human awareness interface to generate the corresponding vibrotactile and visual signals to the human, indicating the level of estimated danger that robot's abnormal state or safeguarding failure might cause. Chapter VI discusses the augmented warning interface development which is based on the vibrotactile and visual cuing approach. This interface relies on data acquired from external sensory unit and safety controller to provide timely tactile and visual information to a human. In this approach it is proposed to minimize the volume of safeguards around the robot and consider more lightened robotic cell where human could enter invisible working zone. Chapter VII elaborates the final safety system integration algorithm. The scenario of the case study is modeled for the robot-human scanning system with the industrial robot application. Chapter VIII overviews the main contributions of the thesis, and provides concluding remarks about the proposed further developments for human–robot interaction system. Directions for future work are also outlined.

Nomenclature

$\mu_A(x)$		Membership Function of the region A
X		Crisp set
K, Ke	[N/m]	Manipulator Interface, Effective Stiffness
x_{ij} , a_{ij}		Elements of the matrix
$\max_j$		Upper interval limit on the scale
$Fi(E, P)$		Ergonomic or Personnel Factor Name
w_i		i^{th} Factor's Weight
v_i		i^{th} Element of the Priority Vector
$\mu_{\max}(F)$		Maximum Importance Factor
dP		Differential change in perception
dS		Differential change in stimuli
a_h	[g]	Head acceleration after Impact
a_c a_i	[g]	Critical, Actual Acceleration (resp.)
f_c, f_i	[N]	Critical, Actual Impact Force (resp.)
L_c, L_i	[m]	Critical, Actual Distance from Hazard (resp.)
Δt	[ms]	Period of impact
$\alpha_L Di_L(t)$		Distance related Danger Index and its weight
$\alpha_f Di_f(t)$		Force related Danger Index and its weight
$\alpha_a Di_a(t)$		Acceleration related Danger Index and its weight
T_i, T_h, T_c, T_s	[ms]	Robot stopping, Human reaction, Control system and Sensory system response Time (resp.)
v_h	[m/s]	Human walking speed (motion)
v_0	[m/s]	Robot initial operation speed
m_u	[kg]	Scalar value of the mass at the direction u
F_u	[N]	Scalar value of the resulted force at the direction u

v'	[m/s]	Robot velocity after Impact
M	[kg]	Manipulator effective Mass
x_r, x_h	[m]	Robot, Human displacements after Impact
w_n, w_d		Natural, Damped frequency of the oscillation after impact
m_h	[kg]	Human Head Mass
ξn		Damping Ratio
$M(q)$ $M_x(q)$	[kg]	Joint and End Effector Kinetic Energy Matrices
$M_{vx}(q)$	[kg]	Mass matrix of end-effector translational response to a Force
J_v (q)	[m/s]	Jacobian matrix associated with the linear velocity of the endffec-tor
J_{v_u}	[m/s]	Row Jacobian matrix of the linear vel. in the arbitrary direction *u*
m_{vu}	[kg]	Scalar value of the effective mass received at the point of impact with linear motion in the direction *u*
V, λ		Eigenvectors, Eigenvalues
$m_{cu}(Di)$	[kg]	Critical mass value in the direction *u* with respect according to the dander criteria *Di*
$M_c^{n\times m}$	[kg]	Diagonal matrix of the critical masses
$x_d, \dot{x}_d, a_d, F_d, \tau_d$ ($x_a, \dot{x}_a, a_a, F_a, \tau_a$)	[m/s, m/s^2, N, N*m]	Desired (actual) characteristics of position, velocity, acceleration, force and torque (resp.)
Ω', Ω		Selection matrices associated with specifications of manipulator motion and forces (resp.)
B, G	N	Vectors of centrifugal and carioles forces (resp.)
$\overrightarrow{R}$	[...]	Generalized vector of the robot related variables
r_n		Robot related functional elements
D^i_R		Domain of the robot relative variables associated with the M_i
$\vec{L}_i$	[m]	Generalized vector of the distance related variables
l_n	[m]	Distance related functional elements
D^i_L		Domain of the distance relative variables associated with the M_i
$\vec{S}$		Generalized vector of the Safeguard related variables

s_n		Safeguard related functional elements
$D_{\bar{S}}^{i}$, SS*i*		Domain of the safeguard relative variables associated with the M_i
D_s		Safety Distance
d1, d2	[m]	Manipulator operating and maximum zone diameters (resp.)
H	[m]	Instrument length
F_h	[N]	Human applied force
Ra	[...]	Robot related actual characteristics
Rd	[...]	Robot related desired characteristics

Abbreviation

HRI	Human Robot Interaction
RIA	Robotic Industries Association
ANSI	American National Standards Institute
DI	Danger Index
ISO	International Organization for Standardization
E	Ergonomic Characteristics
HF	Human Factor
SES	Safety Expert System
SMS	Safety Monitoring System
SMC	Safety Mode Controller
Safeguarding System	Safeguarding System
RC	Robot Controller
HAI	Human Awareness Interface
TP	Teach Pendant
DIC	Dynamic Characteristics
M_i	Safety Mode
P	Personnel Characteristics
KRL	Kuka Robot Language
DoF	Degrees of Freedom
RT	Reaction Time
SDT	Signal Detection Theory
SA	Situation Awareness
L1-L4	Interaction Level
OSHA	Occupational Safety and Health Administration
FTA	Fault Tree Analysis
FMEA	Failure Mode and Effect Analysis
S1,S2	Severe, Not Severe Hazard

A1, A2	Hazard Avoidance likely, not likely
E1, E2	Exposure to hazard frequent, not frequent
R1-R8	Risk Category
HCD	Human Centered Design
PLC	Programmable Logic Controller
PSS	Programmable Safety and Control System
ESC	Electrical Safety Circuit
AC	Alternating Current
DC	Direct Current
ES	Emergency Stop
PRP	Psychological Refractory Period
PWM	Pulse Width Modulation
ASCII	American Standard Code for Information Interchange
LED	Light Emitting Diode
GUI	Graphical User Interface
WSTC	Wayne State University Tolerance Curve
AIS	Abbreviated Injury Scale
HIC	Head Injury Criteria
MAIS	Modified Abbreviated Injury Scale
SI	Serious Injury
Di(HIC)	HIC based Danger Index
Di(N)	Newton's Low based DI
RR	2 DoF Rotational Manipulator
MC	Motion Controller
DIM	Danger Index Monitor
A	Acceleration Controller
FK	Forward Kinematics
R, L, SS	Robot, Distance, Safeguarding related Characteristics (resp.)
D	Domain
WS	Work Station
CoM	Center of Mass
ID	Identification

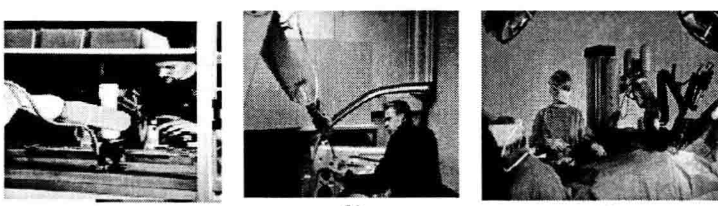
Table of Contents

Chapter I: Introduction

1.1 Human-Robot Interaction Domain

Robots have been successfully employed in industrial settings to improve productivity and perform dangerous or monotonous tasks. Recently, research has focused on the potential for using robots to aid humans outside the strictly industrial environment, in medical, office or home settings.

One of the critical issues hampering the entry of robots into unstructured environments populated by humans is safety, and more broadly, dependability, that incorporates both physical safety and operating robustness. [1], [2] Some robot solutions, intended primarily for social interaction, avoid safety issues by virtue of their small size, mass and limited manipulability. [3]-[5] However, when the interactions also include manipulation tasks, such as picking up and carrying items, assisting in assembling, handling, etc., larger, more powerful robots will be employed. Such robots must be able to interact with humans in a safe and friendly manner while performing their tasks.



(a) (b) (c)
Fig.1.1 Human-Robot Interaction Domains: Manufacture Assistants (a, b), Surgery (c)

The research towards the human-robot cooperation is relatively new, it did not appear in any publications before 1992. A real-world applications of robotics implies using robots in close interaction with humans. Robots are already successfully implemented in many fields performing tasks in close vicinity to human or even physically interacting with them. Examples are: robotics applications in medicine: neurosurgery [6], [7], in orthopedics [8], in physiotherapy [9], in surgery [10] (see Fig. 1.1 c); social robotics developments in domestic application: security robots [11], entertainment [12], education and house cleaning [13], [14]; examples of robots application in space, in a human-rover teams exploring planetary surfaces [15]; and effective presentation as assistants to humans in manufacturing environments. [16], [17], [18] (see Fig. 1.1 a, b) The use of robots as a manufacturing assistances will lead to significant improvements of industrial manufacturing process, partially in terms of increased productivity, flexibility, and humanization of the work place. Robot assistants in manufacturing will accomplish tasks through close interaction with people by supporting and not replacing them. These new generation machines can be viewed as evolutions of industrial and mobile robots and have been under investigation for some time. However, older robots with fewer safety features will still continue their existence and to be used at some applications required human intervention in their operation process. Therefore, an additional safeguarding approach should be developed that wouldn't require an installation of sophisticated safety systems or replacing existed manipulators but provide the reliable and dependable response on the robot related dangerous conditions especially when the task requires a synergy with human workers.

1.2 Research Motivation and Objectives

An extreme degree of automation may not be always the most suited approach for manufacturing. When the production involves a smaller number of units with design variations and increased task complexity, the high cost of infrastructures, reprogramming, and validation all point towards different manufacturing solutions. Robots today are limited in their abilities to perform advanced tasks that require a high degree of perception and skills. These capabilities are still difficult to achieve in a robust and cost-effective way.

Human's sensory/motor abilities, knowledge and skills can be thus effectively combined with the advantages of a robot (e.g., power, endurance, speed, and precision). Working together with human, assistive robots can, in addition to their ability of handling special tasks, cover a broad spectrum of different tasks. During the interaction with people, robots must be able to execute basic performance involving planning, navigation, exploration and manipulation.

The Human Robot Interaction (HRI) area has a widespread field of applications, where collaboration can be carried out at different interaction levels with various extent of danger. Some tasks require a very close human presence or even contact with robot parts. For other tasks, a distant monitoring can be sufficient. In both cases the movements and workplaces of the human and robot can overlap. Working in a close vicinity of robots implies a high probability of an unforeseen contact that may cause pain or injuries to the human body. Thus, it's essential to investigate the body tolerance to these undesirable collisions and to design the human-robot (h-r) coexistent system with this consideration in mind.

The coexistence of humans in robots' operational domains brings a significant risk of dangerous situations for those involved. It is therefore critical that only dependable robot systems are deployed for human-robot collaborative tasks. Safety and reliability is the unified criterion for future technical challenges in the design and control of robots operating in the human environments. Unfortunately, mechanical structures and physical characteristics of most industrial robots currently available on the market are far from meeting these requirements and carry a high risk of causing severe injuries to humans. To insure human safety, it is important therefore to develop a safety system with futures that address the mechanical characteristics of the robot, as well as the safety characteristic of its path planning and control strategies.

The key goals of the research presented in this thesis were to identify the tasks associated possible hazards, to develop appropriate safeguarding strategies, and to build an integrated safety system that would ensure human safety and confidence when operating inside the robotic workspace. With this aim, the collaborative workspace was build, where human safety within the interaction is evaluated by combining the off-line risk assessment, reduction procedures, and the on-line safety monitoring system. The control strategy is addressed via safety modes and danger indices monitoring during the task performance. Safety modes authorization is performed by the Safety Expert System assessments, that implies compliance with the safety and ergonomic requirements according to the identified risk category and interaction level. With the aim to enhance human vigilance and situational awareness during the interaction, a wearable vibrotactile interface is introduced as a complementary personnel protective system. This interface is also integrated into the overall safety system architecture and which operation conforms to the predefined safety rules.

1.3 Safety System Description

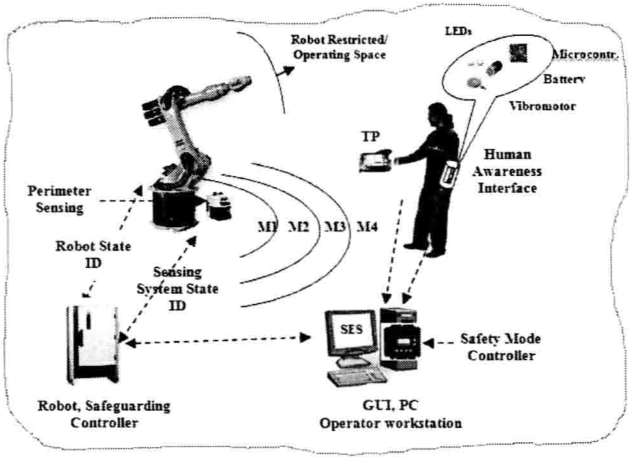


Fig. 1.2 Architecture of the proposed Safety System, M1-M4-safety modes, TP-teach pendant, SES- safety expert system, GUI- graphical user interface

The architecture of the proposed safety system is conceived as an integrated protection system consistent of four levels determined by the very nature of the human-robot interaction. (see Fig.1.2) The first level (L1) corresponds to tasks involving overlapping of the workspaces of the human (operator) and the robot during the task performance, where physical contact is allowed. In the next level (L2), agents are invisibly separated whether by the task distribution or by the defined control strategy. The human, due to the specificity of the task, can carry out his/her task in a very close proximity to the robot. Within this level the human is allowed to enter the restricted workspace, but not the robot operating space. The third level (L3) is located further away from the second level, but an operator may still be within the robot arm's reach and can therefore be exposed to a certain degree of danger or risk of injury. Finally, the fourth interaction level (L4) is defined as the level outside the robot working envelope, but this area is not protected from thrown objects or released energy. Separation between levels depends mainly on the robot structural and operational characteristics and on the task specific characteristics. Some aspects of human physiology as well as psychology (attitude) are also included into the differentiation of the levels.

All robot tasks and human roles are associated with a certain level of interaction enabling to monitor each zone separately by controlling at each time a predefined set of parameters received from the Safety System constituent elements. This monitoring system is called Safety Mode Controller and monitoring zones - Safety Modes. The main components of the integrated Safety System are Safety Expert System (SES), Safeguarding and Human Sensing System, Robot Controller (Robot), and Human Awareness Interface (HAI). All elements are interconnected with the Safety Mode Controller (SMC) which operates according to the safety criteria, predefined for each safety mode (interaction level).

The Expert System together with the off-line task description and associated interaction level provide (i) hazard analysis and risk assessment; (ii) estimates the ergonomic and safeguarding conditions according to the task risk category; (iii) analyses the human factor and cognitive, physical load of the task; (iv) and, as a result, generate a protocol that indicates the system's "readiness" (or not) for the task performance.

Robot critical characteristics are also partially estimated in the SES, where user (designer) specifies a type of a manipulator and its operating parameters. Knowing the interaction level, the task specific, the human role and the robot physical characteristics, safety modes can be adjusted to control the corresponding zones according to the safety criteria. The closer the interaction is the more restrictive the requirements to the operating parameters are. Safety criterion is mainly based on the developed in the research Danger Index metric, which consists of force/acceleration and distance danger evaluation measures.

A distance from the hazard is evaluated by proximity sensors (scanner, cameras, etc.), capturing the operator location at each moment. Monitoring parameters and operating algorithms are changing depending on the currently activated Safety Mode and ambient conditions. To hold a safe distance between the human and robot is a general safety criterion, that is a default requirement for non-contact interactions ($Di_{L1\text{-}4}$). Monitored distances for each safety mode were identified based on the robot structural and operation characteristics, and the human factor physiological and psychological demands: visual, reach (from ergonomic guidance [64], [116]), "feel safe" (from experimental data [62], [70], [71])). (see Fig. 1.3, Li)

The force/acceleration related index can be considered within all levels when there is a probability of impact. Within this criterion also 4 levels were defined, where in the case of an unanticipated contact, the injury or pain can be caused to a human. The first danger criterion (Dif_1) is associated with "no pain" level, second (Dif_2) with "no injury", and the last two (Dif_3, Dif_4) can be called "tolerable injury" (experimental data [60], [118]-[132]). Abbreviations were chosen in compliance with the corresponding interaction levels, where these criteria can be applied. The introduced index mainly depends on the robot working characteristics as speed, effective mass, interface stiffness and impact force, however, other parameters can be added into the monitoring algorithm strategy. (see Fig. 1.3, Ri)

The Safeguarding systems that were chosen with the aid of the Expert System assessment techniques, should be also controlled by the monitoring system. Some protective means remain the same on several levels of interaction; others require some changes in operating parameters. Therefore, there is no defined boundary in the safety elements transition control algorithms and their sets of characteristics are overlapped. (see Fig. 1.3, SSi).

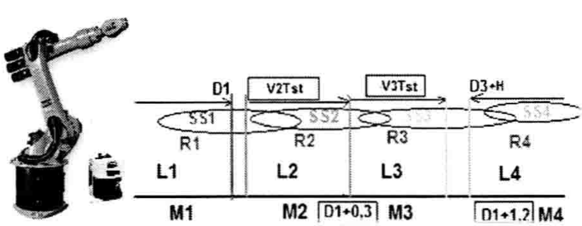


Fig. 1.3 Safety Mode Controller Operating/Transition Paradigm

Once the safety mode Mi has been activated all monitoring elements should comply with the rules identified in the safety protocol at each moment of time and forced to stop (or act in conformity with a safety algorithm) in the event of any inconsistency.

The proposed human warning system (Human Awareness Interface), mounted on the individual wrist and interconnected with the Safety System, suppose to alert an operator about the system current state by imparting vibrotactile and visual cueing. Therefore, even being destructed or unaware about a hazard, the human operator will be able to react quickly and safely according to these signals.