Creating an Active Awareness System for Humans in Robotic Workcell

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Abstract: This article is devoted to the problem of human's security and safety at the time of any interaction with robots. We already discussed robot system reliability in the previous paper [1], now we emphasize the role of attention and human awareness with respect to the robot's performance in vicinity. We analyzed human's cognitive and physical abilities in ambient environment perception with the aim at effective warning system implementation. We introduced warning system interface on the basis of vibrotactile cuing, proposed an algorithm for robot controller and interface that impart tactile and visual information to human basing on data acquired from external sensory unit.

Keywords: Human-Robot Interaction,awareness, vibrotactile stimuli

1 Introduction

More than 40 years have passed, since robots have been introduced for industrial applications. Robotics technology, which has been matured enough to be applied to several systems in our daily life, is expected to be one of the key technologies for the aging society.

In industrial applications, robots usually isolated from human to ensure his/her safety, however, some advanced tasks, where robots cannot perform alone without superior human's capabilities, there is a necessity in the work spaces intersection, where conventional safeguarded systems are not sufficient anymore.

According to safety standards robot must be fully isolated from the other machines and any interactions with human are allowed only if the robot power is cut off, and the performance is interrupted, what usually brings to losses in productivity. Robotic cell usually occupies significant amount of space, hard for access and visual monitoring, often safety systems and controls are complicated in installation and usage, and at the same time don't provide absolute security and safety. There is a definite need to develop advanced dynamic active safety system where human's presence and work would be fully protected and convenience provided. Nowadays robots can be either slowed down or stopped if hazardous situation has been identified [2], moved to evade contact [3], or impact force can be minimized if contact occurred [4]. There are also examples of robot's physical redesign using visco-elastic covering [5], spherical and compliant joints [6], or distributed actuation [7]. However, to redesign already existed robots or change the control is not always possible solution in some applications, it requires time, additional costs and instrumentations.

In spite of the training programs, warnings and experience people incline to commit mistakes (errors), whether due to inattention, poorly designed workplace or accidentally because of the faulty cognition, perception or unawareness about ambient environments: robot's current state can be misperceived, speed and range of movements underestimated, warning sights unnoticed, etc.

In our approach we propose to minimize the volume of safeguards around the robot and consider more lightened robotic cell where human could enter invisible working zone, but where not only the robot would be aware about this presence, modifying its state, but also the human would 'feel' the level of danger depending on the current distance against the manipulator. Human safety will be provided by means of advanced warning system that consists of multisensory safety system and human active interface on the base of vibrotactile stimuli.

2 Human's Awareness and Modalities

Study of cognitive science would be essential to make better understanding human's mechanism of attention and utilize to reduce their errors. People have several cognitive abilities to perceive environment and process information about it. We receive the information visually or via an auditory organ (perception), understand and interpret the meaning of the perceived information and make decisions interacting with the knowledge stored in the memory system (cognition). (See Fig. 1) There are various levels of perception that depend on the stimulus and the task confronting a person. The most basic form of perception is a simple detection, the most complicated are identification and recognition. We perceive an environment via internal sensors, then this visual, auditory, tactile, etc. information is synchronized, processed in the brain and only then we evaluate the response according to the chosen behavior.

The act of perception involves prior experiences and learned associations. However, on abilities in perception nature of stimuli, attention and awareness have significant influence. Even the act of the simple detection depends on the quantity and quality of the stimuli and an attitude toward them.

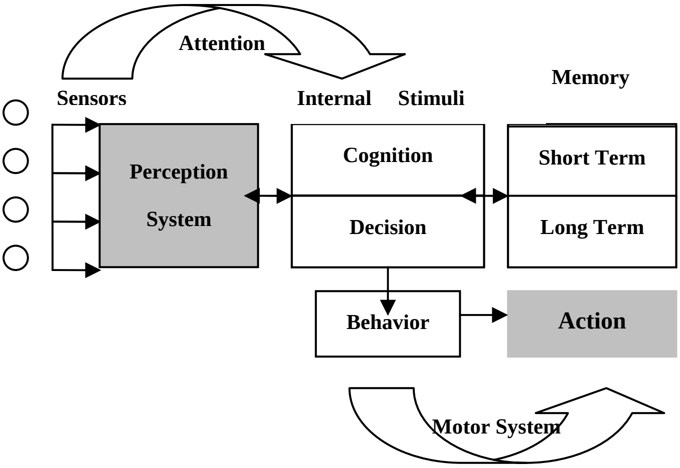

Figure 1
Human cognitive model

2.1 Awareness

Usually awareness involves matching information received from the human senses to the prelearned situational templates that allow us to understand the situation and predict what is likely happen, unfortunately we have some internal cognitive limitations and very sensitive to the external factors.

In fact, the person is aware that the stimulus will occur within a short time and within a specific spatial area. However, most of the time, several different stimuli may appear requiring different responses and the more natural the relationship between stimuli and responses, the faster reaction time (RT) and more accurate action will be. Our expectations have profound impact on the performance, they can be related whether to a robot state, range of motions, or to warnings and displayed information. Important concept in this issue is compatibility of stimuli and responses to human expectations. [8]

There are also significant limits on people’s ability to divide attention across multiple aspects of the environment, particular within simple modality, such as vision or sound. Humans tend to lock in on certain aspects or features of the environment, they are trying to process and drop their scanning behavior. However, the human perceptual system can be more sensitive to certain features, so-called salient factors: loud noises, large shapes, things that physically have the advantage to catching a person’s attention. By understanding and studying these natural responses more closely we could develop a concept of workplace and safety system design where human performance, attention and awareness would be enhanced.

2.2 Modalities

When we design human working space or warning system with the aim to optimize his/her work or effectively attract attention to particular case we need to take into consideration human's natural capabilities and constrains. Among the human sensing capabilities we highlighted 3 main forms:

2.2.1 Visual Sensing

The visual sensing system is very well developed. The structure of visual stimuli is well understood, and display technology can produce extremely expressive stimuli. However, one aspect that limits its general usage is the need for the user to attend to the visual stimulus. If the user is looking in a different direction, or is preoccupied with another visual task, stimuli can be missed. Visual stimuli are generated by combinations of varying hue, saturation, and intensity. It is often difficult to direct human attention rapidly toward appropriate areas of space. For instance, vision as a sensory input channel may become overloaded by the numerous parallel sources of information. Human cognitive system has a limited processing ability. Therefore, in general, human directs attention to only one of the objects presented. Asa result, for instance, during warning system design we need to take into account that the background color and ambient illumination can interact to influence the ability of people to detect and respond to lights of different colors. In the case of flashing lights, the rates of about 3-10 per second (with duration at least 0,05 s) have been recommended for attracting attention. The spurce should be situated within 30^{o} of the human normal line of sight and subtend at least 1^{o} of visual angle, stimulus presented in the peripheral field of view (45^{o} from the fovea) are responded to about 15-30 ms slower than the centrally presented. [8]

There is potential competition among visual attention and other cognitive tasks for limited working memory capacity and additional sensory cues may reduce the demands of visual attention on working memory. So as a consequence aiming at improve human awareness and augment human sensitivity to stimuli we need to compensate visual cues with complementary ones (tactile, auditory) and without any signal suppression.

2.2.2 Auditory Sensing

The sense of hearing is very developed as well. Humans are sensitive to temporal, spatial, and waveform characteristics of audio signals. Audio cues are omni-directional in the sense that the listener does not need to be facing in a certain direction to attend to the sound. A sound signal is made up of waves of varying frequency and amplitude. This makes the general use of sound attractive for alerts, as well as for information display. It was discovered that the most noticeable audio signals are: beep with frequency 425 Hz and yeow (descending change in frequency from 800 to 100 Hz every 1.4 s). Reaction time to these signals decrease with increased signal intensity. However, the high-intensity signals elicit a startle reflex, which may be helpful only if the same response is demanded. We also should take into consideration the fact that the frequencies between 500-3000 Hz are most sensitive for the human ear and that the smallest frequency detectable is 28 Hz. [9]

2.2.3 Tactile Sensing

The sense of touch is arguably the most complex of the three modalities. This is partially due to several types of sensations all being attributed to this single 'sense'. There are several kinds of receptors, each allowing us to sense a different type of stimulus, such as thermal properties, vibration of varying frequencies, pressure, and pain. The sense of touch is the only one where the entire system conducts both sensing and actuation. [10]

The tactile sensory threshold is defined as the minimum stimulus intensity that is barely perceivable by a human. It is one of the most basic measures of human perception. The sensitivity vary depending on experimental conditions such as contact area, contact force, contact location, temperature of the skin, use of a rigid surround, stimulus duration, the participant's age, etc.

Importantly, when we design warning interface with multiple channels of auditory, visual and tactile signals we should take into account that stimulus requiring individual responses should be separated temporally (more than 0,25 s) to avoid overlapping. In addition, their number should be reduced, actual important signals be more intense and uncertainty of unnecessary signals reduced.

3 Active Interface. Vibrotactile Stimuli

Our aim was to design attention-aware system that would activate human's tactile and visual sensing, attracting attention and augmenting awareness about possible hazard in vicinity during work performance inside the robotic workcell. To do this we decided to implement vibrotactile stimuli, attached to the wearable device. Vibration with different intensity and flashes provides human with complementary information about possible hazard in proximity. This knowledge enables to take quick actions and avoid unwilling consecuances.

We have chosen this method of tactile cuing because this sense is the most reliable among the others modalities. The risk of signal overlapping is very low, and the skin sensitivity for the local signal exposure is very high. Moreover, it was studied that human's reaction time on tactile stimuli is much smaller with comparison to the audio and visual signals; don't have neither any spatial constrains nor dependance on human's current visual and audio attention.

3.1 Related Studies

A number of research groups have been exploring the use of additional stimuli modulities transmitted through different divices for improving human's capabilities in performance.

The effectiveness of tactile cues for spatial orientation, navigation, and situational awareness was demonstrated from the studies on pilots and astronaut [11]. In experiment conducted by Ho, et al. [12] vibrotactile display with two tactors attached to a belt fastened around the participant's waist was used to provide additional stimuli to drivers. The tactors were driven by sinusoidal signal at intensity sufficient to deliver clearly perceive vibrotactile stimuli. The results revealed that participants responded significantly more rapidly in the cued condition than in the uncued; results also highlighted a significantly bigger safety margin with the vibrotactile cuing. In another research Tacta ArmBand system was deployed. [13] To support the delivery of vibrotactile stimuli, this group designed the TactaBoard system and looked at determining the limits of perception in terms of vibration intensity, location discrimination and wearable system application for information transmission. There was also experiment where back of a person was chosen to be interfaced with a haptic display consisted of 3 by 3 tactor array to impart tactile information to user and to form multiverbal interfaces with other existing visual and auditory interfaces [14]. Studies were related to attentional and directional cuing. During research it was measured to what extent haptic cueing can affect an observer's visual spatial attention and was found that reaction times decrease with the valid haptic cues and increase with the invalid ones.

Thus, it was showed and experimentally proved that additional stimulating cuing is effective method to enhance human's attention and accordingly performance. Depending on the application and signal nature we may attract (or distract) people, make them more attentive or vice versa confused about ambient environment. Therefore it is very important to design and allocate signalizing elements properly considering all possible effects which they might have on human's perception.

4 Design

In proposed interface we have chosen the wrist of a person to be stimulated with tactile stimuli that impart non-verbal information to its user about close danger, i.e. robot in vicinity. For a tactile attention cueing, we propose to use one or two tactors attached inside of the band (see Figure 2).

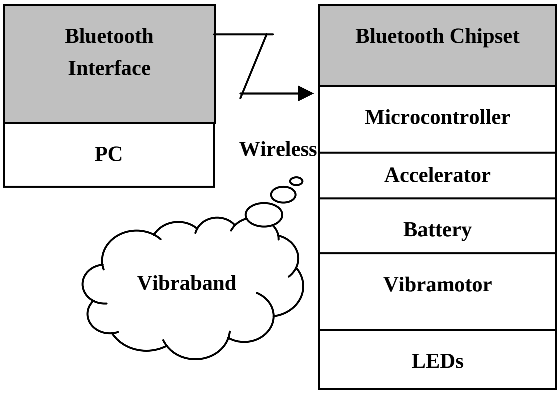

Figure 2
Vibraband structure and connection

The entire system consists of a host computer (PC) to send control commands via wireless interface, a microcontroller that transfers converted signals with predefined output voltages to vibromotor, accelerator, battery, and LEDs with 3 colors for visual signal indication. The system runs from battery power, and uses a Bluetooth wireless serial bridge connection to provide control from the host computer. The frequency of the vibration can be changed with voltages, thus we can vary the intensity of the signal, color of LEDs and control strength. For human skin (hand) the most sensitive frequency band was found between 200 Hz and 300 Hz [15]. Figure 3 displays this assumption with tactile perception for the hand, detection threshold and sensation level data for continuous sinusoidal vibration

However, for the moving person this frequency won't be enough and we should increase this magnitude to 500-550 Hz. Pulse interval was defined as 500 msec (for users can easily recognize it) [16]. This device, placing on the human's wrist, activates the vibration that imparts so-called precollision or warning information when a human is detected in the robot's (scanner) work zone with a high probability of impact. Figure 4 shows employed elements and connections between them.

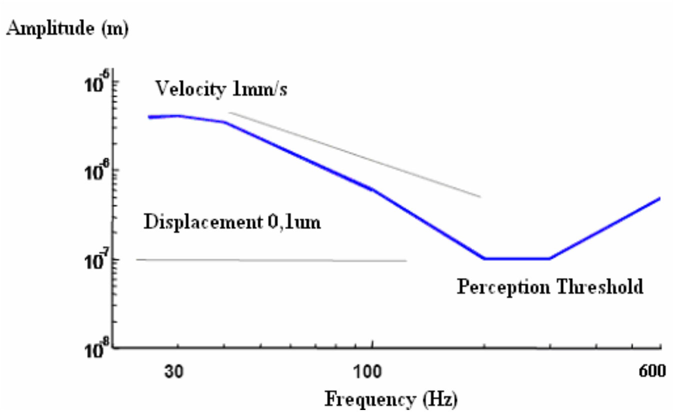

Figure 3
Human hand sensation threshold

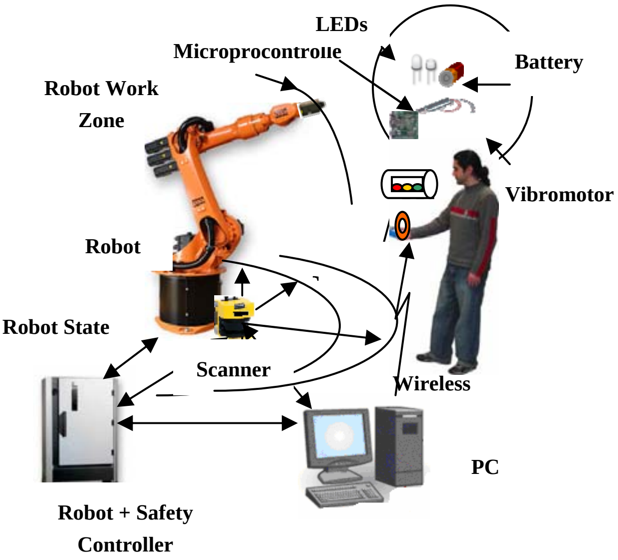

Figure 4
Elements and Connections

4.1 Robot Safety System

When robots are assigned to work in proximity to humans they should meet safety requirements related to the application. To comply with the safety regulations we use the robot with certified safety system and sensory feedback to monitor its normal operation and working space with human detection in it. Our robot comprises its own embedded safe technology that monitors velocity and acceleration of the axes and enables a safe operational stop of the robot.

The working space of the linear unit is limited by adjustable software limit switches for all axes backed up by mechanical limit stops in case these limit switches are overrun. The motion of the robot in space always corresponds to that calculated by the controller. The current axis positions are then compared with the saved reference positions, and loss of mastering in the event of a fault is detected immediately. The module responsible for monitoring the safety functions is designed using failsafe technology with built-in redundancy. Based on the reliably determined position values for each robot axes the limit values of the ranges for individual axes and axis groups are monitored on the safety module, along with their velocity and acceleration. The safety-relevant parameters and limit values are configured directly in the robot controller.

4.2 Sensory Safety System

For detecting humans in working zone we propose multisensory system consisting of ultrasonic sensory system mounted on the robot’s wrist, that enable to detect objects very quickly from the close distance and to avoid collision with them by sending stopping signal on the robot controller. Ultrasonic sensors operate by using sound waves to detect targets. They generate a short, intense sound burst from a piezoelectric transducer, which is reflected back by the object. The sensor determines the distance to an object by measuring the time that elapses between the emission of an ultrasonic burst and the arrival of the echo reflected by the target. This sensing method ensures reliable operation regardless of the object's color or opacity. Other safety unit for human detection is scanning range finder that monitors the surface around the robot within its reachable range. Scanning Laser Range Finder (SLRF) is wired directly to the robot controller. We chose SLRF with wide scanning window high accuracy and its scanning speed. The scan area is defined as 240º semicircles with maximum radius 4000 mm. Scantime is 100 msec/scan. Pitch angle is 0.36º and sensor outputs the distance measured at every point (683 steps) [17]. The principle of distance measurement is based on calculation of the phase difference, due to which it is possible to obtain stable measurement with minimum influence from object’s color and surface gloss. Scanner constantly monitors the surface, when the detection of object take place derived distance passes directly to the controller.

We also proposed to use stereo camera that would grid the surface similarly to the scanner, but with a larger zone. However, application of too many sensors can be resulted in signal overlapping and reduce the speed of signal processing in controller. The choice of safety equipment is not final, and requires more investigations and trial data to evaluate effectiveness and compatibility to application.

5 Distance Definition and Control Algorithm

The ranges of controlled distances to the robot were evaluated from the investigations provided by various researches in term of human's psychological attitude toward robot spatial motions, physiology, cognitive capabilities of the human (how much time we need to perceive and react on stimuli and anticipate hazard); robot system characteristics: maximum stopping time, speed, acceleration, range of movements, operational mode, etc.; safety sensors characteristics (range of operation, accuracy, response time.) For the criterion of the safe distance definition, we also examined the human spatial behavior during human-human interaction [18]. In this work the human-human interpersonal space was divided into four regions marked by the distance from the each person: 1) Intimate space (0–0.45 m): space reserved for interaction with close friend. Within this distance interaction with robots possible only if special operational mode is available or safety features to robot are embedded (compliance, force control, sensors, soft covering, etc.); 2) Personal space (0.45 m–1.2 m): distance for interaction with a friends. This zone we usually use for robot teaching and team work, where robots are assigned to assist humans or vise versa; 3) Social space (1.2 m–3.6 m): this distance is usually kept for a non-friend interaction (business, formal or casual acquaintance interaction). In robot application this area is kept for distant observation, teaching, monitoring tasks, etc.; 4) Public space (>3.6 m): in general this space is set for public speaking with where personnel contact is avoided. With respect to robotics distant monitoring and work observation can be carried out here. (See Fig. 5)

Drawing a parallel with a human-human interaction we defined that the distance people prefer to keep from the robot equal to those that they usually hold interacting with unknown person, not too close, distance enough for auditory conversation (personal space, 0,5-1,2 m). However, if there is a necessity in physical contact (peer to peer operation) this value can be diminished to 20-30 cm, but for operating within this area special safety rules, guidelines and additional guards should be considered.

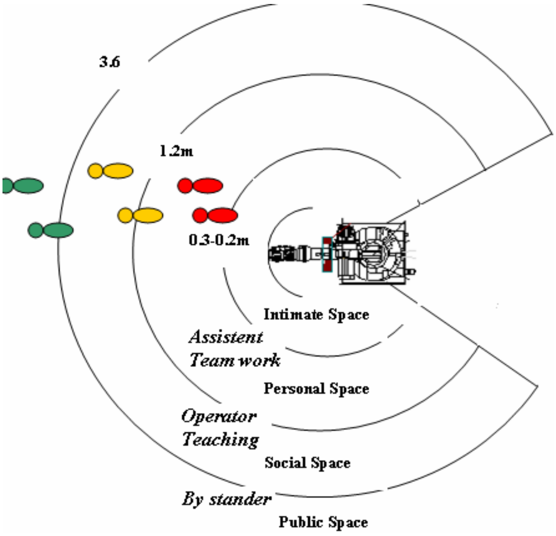

Figure 5
Interaction workspaces

5.1 Algorithm

The scanner range finder continuously monitors the robot working zone within the maximum range. Information about detected object i.e. measured distance directs to the robot controller and microcontroller of the vibraband. According to this value and other characteristics related to the robot state at the moment on the base of algorithm below robot and human interfaces (VB) change their functional conditions following the frame deployed further. When human approaches the robot within the distance smaller than ‘public space’ (225 cm), robot’s speed should be decreased to the safe value (150 cm/s), and low frequency signal transmitted to the vibraband. LEDs are indicated with a yellow color. Robot’s movements should be smooth and unlinear, working zone is restricted by: software, mechanical safety brakes. Robot’s trajectory is predefined to each task and any changes in joints’ angels mean failure and activate signal to stop any motions. When human approaches the robot within the ‘social space’ (110-70 cm) the intensity of the signal increasing thereby attracting attention to a hazardous area, LEDs are indicated with a red color. When human approaches the robot within a critical distance (>30 cm) emergency stop is activated.(See Fig. 6)

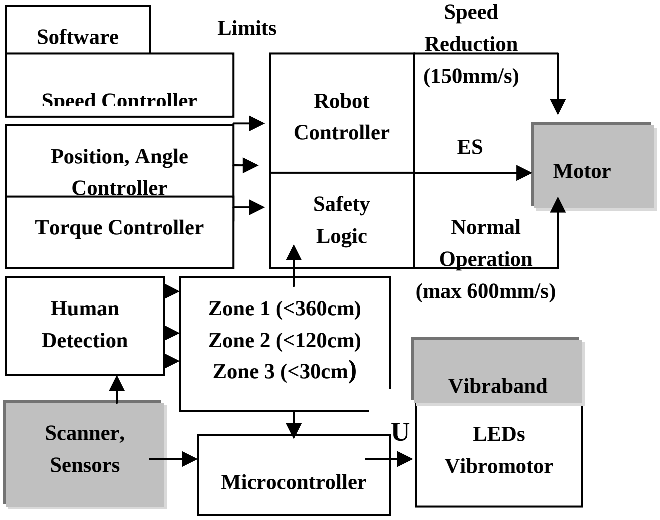

Figure 6
Control Algorithm

Robot controller constantly receives information from sensors about Robot current state from speed, acceleration, torque controller and environment (laser scanner finder, external sensors). Combination of this information with the safety logic generates corresponding signals to the motors and/or to the microcontroller of the activibroband system. Table 1 below represents a programmed functional logic for the robot controller and microprocessor by means of KRL and Delphi languages.

Table 1
Programmable logic for RC and VB Microcontroller

Frame Logic for Robot Controller (KRL)	Frame Logic for Microcomputer (Delphi)

If D<=360 AND D>120 Then
$VEL.CP = 450
Else If D<=120 AND D>30 Then
$VEL.CP = 150
Else If D<=30 Then
$VEL.CP = 0
Break ; Emergency Stop
EndIf
	Procedure CheckDistance(D : Integer);
	begin
	If (D>=120) And (D<360) Then
	Vibrotactile(200, 0.8, clGreen)
	Else If (D>=70) And (D<120) Then
	Vibrotactile(300, 1.2, clYellow)
	Else If (D<70) Then
	Vibrotactile(500, 1.6, clRed); end;

Conclusion and Future Work

The increasing provision of complex technologies means that human may become increasingly distracted. In guidelines for robotic safety it states: 'Audible and visible warning systems are not acceptable safeguarding methods but may be used to enhance the effectiveness of positive safeguards…' [19]. Our proposed warning system can be defined as visibly-tactile, and with compliance to the statement above cannot be considered as full right safeguard system, but we convinced that the idea of implementation this kind of instrumentation will significantly increase human's attentive qualities and help to respond on dangerous situations more accurately and quicker.

Following this rule we agree that warning a human by means of tactile and visual stimuli it is necessary but not sufficient method, therefore additional measures should be carried out where robot's hazardous characteristics would be taken into account. Also the whole workplace should be organized so that human's attentive capabilities, awareness, cognitive process would be enhanced, irrelevant information filtered and removed before it reaches the brain. In our future work we are planning to investigate the effect of directional cuing, by means of which humans would perceive incoming tactile information that indicate not only the close hazard but also its spatial location.

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