

## Journal of Robotics and Mechanical Engineering Research

### Classification of Causes of Errors in the Human - Robot System

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**Article Type:** Research, **Submission Date:** 02 February 2018, **Accepted Date:** 10 March 2018, **Published Date:** 18 April 2018.

**Citation:** Aleksandar Zunjic (2018) Classification of Causes of Errors in the Human - Robot System. J Robot Mech Eng Resr 2(2): 7-13. doi: <https://doi.org/10.24218/jrmer.2018.26>.

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#### Abstract

The very first classification of causes of errors in the human - robot system has been presented in this paper. This new model of error classification in the human - robot system has a global character. This means that it includes the causes of the errors of the individual components of the system, but also the errors that result from their interaction. The model also includes all the factors surrounding this system, which can act as the cause of errors in the human - robot system. This model distinguishes five main groups of causes of errors, described in the paper. The classification of errors in the human - robot system has great importance. It can serve to designers as a guide or reminder on factors that should be taken into account during designing, in order to reduce the errors in the human - robot system. In addition, this model can serve to assess the efficiency and possible causes of accidents in the human - robot system. Certain general solutions for the reduction of causes of errors in the human - robot system are also presented.

**Keywords:** Robot, Human - robot interaction, Errors, Error classification, Ergonomics, Human factors, Safety.

#### Introduction

Human - Robot (H - R) system consists of one human or group of people who control the operation of a robot or a group of robots (see Figure 1). An error in the human - robot system represents a deviation in the execution of the task, which leads to a deviation in the fulfillment of the goal that this system should achieve. Although it could be expected that with the advancement of science the number of errors in the human - robot system decreases, this is not the case. One of the main reasons for the existence of errors in this system is the complexity of modern technology, which has a large number of options, whose states it is necessary to involve and control. Improvement of the robot is conditioned by the change of its components. Each new component becomes a potential cause of an error. Therefore,

each innovative component should be integrated into the system so that it does not pose a possible cause of errors in various conditions of use of robots and for different tasks.



**Figure 1:** An example of the H - R interaction where a real-time human control of robot welding is presented

Each error has its own cause. There are situations where one error can have several causes. Since there is an extremely large number of human-robot systems, there is an extremely large number of possibilities for the appearance of errors, especially when considering the diversity of human and robot interactions. In view of this, it is not easy to list all the possible causes of errors in the human - robot system. However, it is possible to classify the causes of the errors in the human - robot system, which will be done here.

#### Classification of the Causes of Errors in the H - R System

When classifying the cause of the errors in the H - R system, it is necessary to take into account all the necessary factors that may cause an error in the functioning of this system. This means that for this purpose it is not enough to just observe the separated components of this system and consider the possible causes of the errors of the isolated components. In connection with this,

in [1] various modalities of interaction between the teleoperator and the robot are presented. Different modalities of interaction between human and robot can potentially cause different errors in the H - R system.

In the literature, the previously performed classification of the causes of errors in the human-robot system cannot be found. In order to comprehensively identify faults in the H - R system, it is necessary additionally to observe both components of this system in the interaction. In addition, all other factors that surround this system, which can lead to the occurrence of an error in the H - R system, must be taken into account. Starting from this point of view, the causes of errors in the human - robot system can be classified into the following groups (Figure 2):

1. Personal causes of errors, in which some characteristics or a certain state of the operator or user appear as the cause of an error.
2. Causes of errors that originate from inadequate/imperfect robot design.
3. Causes of errors that originate from the conditions of the environment in which a human - robot system performs the task.
4. The causes of errors that originate from an inadequate technological process, which relates to the procedure of performing the task in the human-robot system.
5. Causes of errors that originate from other persons, with whom the person who manages the robot exchanges information.

The main causes of errors in the human - robot system will be described and explained below. In addition, a general approach for reduction of errors in the H - R system will be presented.

### Personal causes of errors

Personal causes of errors are originated from an operator which controls the operation of a robot, or an user that a robot uses for a particular purpose. It is necessary that the possibilities of a human be aligned with the properties and characteristics of the robot. For this reason, the personal characteristics of a human such as intelligence, cognitive ability, various specific abilities, perception, attention, psychomotor coordination, and stamina play an important role in managing the robot. If these features are not matched to robot characteristics, there is a potential for error occurrence. In addition, certain human states may also be

the cause of an error. Fatigue, injuries, the effects of narcotics, the therapeutic condition, and the like can also be the cause of an error in the human-robot system. Human factor errors in the human - robot system are appeared mostly due to inadequate readings from displays, errors in the selection of the control devices, errors in the direction of the movement, incorrect interpretation of the signal, inadequate interpretation of complex information, forgetting, panic, stress, neglect, bad organization.

Depending on the classification criteria, operators' errors can be further divided and classified into a number of groups. According to Bedni, the operator's errors can be divided into sensory, logical and motor [2]. In the human - robot system, sensory errors are the result of inadequate signal perception, both in the immediate and remote working environment of the operator. These mistakes can occur as a result of a particular state of the operator, fatigue, stress, monotony, illusion, insufficient training. Logical errors are the result of personal factors that affect the inadequacy of estimation in decision making. These mistakes are most often made as a result of inexperience, ignorance, wrong thinking, but also a deficiency of time. Motor errors are the result of inadequate reactions and faulty movements. These errors are especially evident when there is an inappropriate arrangement of control devices on the control panel, due to insufficient training, inexperience, reduced abilities or undeveloped skills. In addition, motor errors can be generated further by inappropriate operating environment conditions, by the existence of fatigue of the operator, and the like.

Swain and Guttman, on the other hand, errors of operators related to discrete action classify into: errors of omission, errors of commission, sequence errors and timing errors [3]. Errors of omission relate to a failure to do something, for example, an important step (that has not been implemented) is forgotten in the execution procedure. Errors of commission refer to an improperly performed action during execution, for example when an operator that manages the movement of a robot instead of a mild move of a joystick moves the joystick more than it needs, causing the wrong robot movement. Sequence errors represent a subclass of errors of commission. They relate to the changed order within the set of actions that are necessary for the execution of certain activities. Timing errors are also a subclass of errors of commission. These errors occur when the operator fails to perform the command in the predicted, or allowed time period.

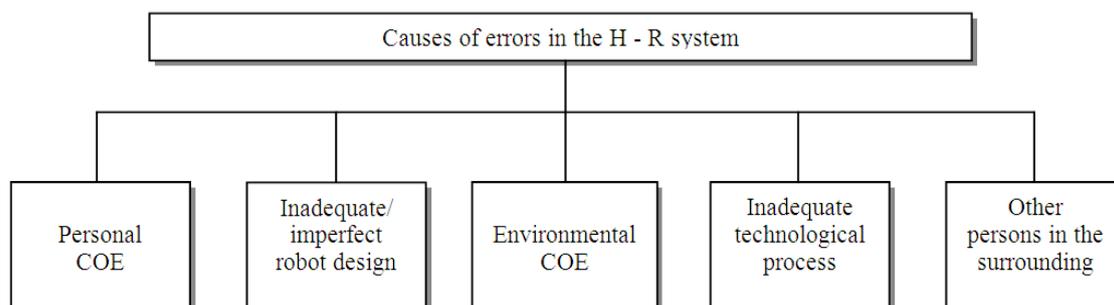


Figure 2: The new model for the classification of causes of errors (COE) in the human - robot system

Reason further errors of operators classifies into errors of routine operations, errors of non-routine operations and errors of deliberate violation of the rules [2]. Errors in carrying out routine operations can occur even in the performance of the usual jobs of experienced operators, if for various reasons they fail to notice a significant change in the working process (robot environment). Mistakes in performing non-routine operations are most commonly caused as a result of ignoring or disregarding general rules, procedures and regulations or their forgetting. Errors arising from deliberate violation of procedures are the result of the execution of improper and inaccurate acts.

#### **Causes of errors due to inadequate/imperfect robot design**

Robot design as much as possible should be in the accordance with user traits. In Zunjic[4] it is described how the robot design can affect the operator's performance in the human - telerobot system. A special problem are the mistakes in the design of robots [5] that can pose a safety problem. The interaction with the robot is accomplished above all through the indicators, displays and control devices. Failures in designing of these parts of a human-robot system are a common cause of errors. Also, the dimensions of a robot and some of its parts should be in accordance with the anthropometric characteristics of humans in order to reduce the possibility of the appearance of errors (for example, an omission in servicing the robot due to the inaccessibility of some of its parts). If the components of a human - robot system are designed to induce sensory or mental overload of the user, errors in the work are inevitable. Additionally, if the robot is not designed to be safe, appearances of errors are possible, which often lead to accidents.

There are a number of different causes of errors that may result from an inadequate or imperfect robot design. Some of these causes of errors are more often considered than others in the scientific literature. Some authors classify causes of errors in the design of robots, or only distinguish separate classes of errors in design, thus identifying the causes of these errors. Sometimes the terms that are used by different authors to classify errors related to robot design have the same or nearly the same meaning, especially when they refer to close terms or phenomena that they describe.

Regarding the above, Whitney et al. [6] divide robot errors into geometric, which are caused by mechanical - geometric imperfections (such as imprecise link length and assembly misalignment [7]), and non geometric errors, which result from gravity (that cause the structural deformations), backlash, joint compliance and gear errors. Ma et al. [7] robot kinematic errors classify on static and joint-dependent. These authors also consider that the aforementioned geometrical errors are the main cause of positioning errors in industrial robots. Considering the gear transmission errors, Slamani and Bonev [8] have found that structural deformations, eccentricity errors and backlash are the most important sources of errors affecting the accuracy of the industrial robot. Use of gears cause nonlinearities in the

operation of the drive system, and further, these nonlinearities can be the cause of the errors in robot joints [9]. Non-uniformities in bearing systems are also the frequent cause of errors [7,8]. In the literature [7] is also mentioned the division of errors that are the consequence of robot design on constant kinematic errors and complex kinematic errors. In addition to the mentioned, in [10-12], in the description of errors of robots, a division into the positional errors and the orientation errors is used.

One of the most general classifications of robot errors is the classification that has been given in [13]. Nakamura et al. all the causes of robot errors classify into four groups: execution errors, planning errors, modeling errors and sensing errors. From the aspect of design, execution errors are most often caused by the existence of some error in the robot mechanism. Although planning errors due to their general character may in some circumstances be characterized as design errors (especially in software domain), they will be explained below in the section dealing with the causes of defects that arise due to inadequate technological process. The same goes for modeling errors. From the aspect of design, sensing errors occur when the characteristics of the sensor system of the robot do not correspond to the required accuracy of the work.

Another global division of the causes of errors in robot design can be mentioned. These are hardware, software and electronic errors. Although these errors can be seen as errors in the design of robots, they also can be regarded as errors in the technological process, depending on the adopted point of view. For example, one can talk about software design. However, since the software contains a procedure for executing a robot task, errors in the task execution process can be considered as errors in the technological process. Similarly, some errors that are manifested as hardware errors can also be seen as errors in the technological process, e.g. those that are related to the calibration of certain hardware components.

#### **Causes of errors that originate from the environment**

Unsuitable environmental conditions are the cause that in some cases can lead to the errors in work. Exposure to vibrations, high acceleration, extremely high and low temperatures, work of the operator in noisy conditions, under low illumination conditions are factors that adversely affect the human - robot system, thus creating the basis for the occurrence of errors. Great changes in temperature and inadequate humidity of the air for the work of robots can cause execution errors [13]. In connection with the aforementioned, Salamani et al. [14] have noted that thermal expansion after a cold start has an impact on the occurrence of errors in work of industrial robots.

In addition, certain elements from the environment can negatively affect the comfort of the operator, which can be reflected in the occurrence of an error. If, for example, a chair that is intended for work of an operator is inadequately designed, due to long-term work it can cause discomfort and pain, which

can lead to a reduction in attention and the need for shorter or longer working interruptions, which can further be reflected in the occurrence of an error in the human - robot system.

### **Causes of errors that originate from an inadequate technological process**

The technological process here implies the way the human - robot system operates (a prescribed methodology, ie a procedure), which is created in order to achieve the goal of the system. The causes of errors that originate from an inadequate technological process are often related to incomplete or unclear work procedures or, in some cases, to the absence of such procedures, especially when it comes to specific and unforeseen situations. If, for example, the pace of work dictated by the envisaged technological procedure is such that it exceeds the operator's sensory and mental capacities, then the probability of occurrence of an error is increased. If, on the other hand, the tempo of work is extremely low so as to cause boredom or drowsiness of the operator, there are also conditions for the occurrence of faults in the human - robot system. Procedures and instructions that are not written in accordance with ergonomic principles related to legibility, readability and visibility often lead to errors, whereby the consequences may be catastrophic, especially in complex and expensive operations.

Execution errors (mentioned earlier) also can be caused by improper maintenance of robots, which can be the result of an inadequate technological procedure. Planning errors (also mentioned earlier) can also be classified into a group of errors that originate from an inadequate technological procedure. This error occurs when the interpretation of the system that is used in the computer software does not represent a real system strictly [13]. The cause of the error is mostly a mistake in the setting of a threshold or a parameter during the planning process. Modeling errors occur when the geometry model used in the computer software does not represent the real objects precisely [13]. Since this type of error is directly related to the task execution procedure, it also belongs primarily to the group of errors that originate from the inadequate technological process. Also, inadequate calibration specified by the technological procedure can be the cause of sensing errors, as well as orientation errors.

### **Causes of errors that originate from other persons**

The causes of errors that originate from other persons are most often associated with various aspects of human-human interaction. Such a type of interaction, if at the same time takes place with the human - robot interaction, acts as a disturbing factor, which negatively affects the perception of workers, information processing and the management process itself, which can cause an error. In addition, the exchange of misleading information in the human - human system regarding the functioning of the human - robot system can also be the cause of the error. The cause of the error may also be the physical disruption of the operator who controls the robot's work by another person.

A mistake that arises from other people may also be the depriving the necessary information that is required to the operator to manage the robot or delay in delivering that information. "Common ground" refers to the beliefs, knowledge, attitudes and goals that group of people share [15,16]. Common ground is essential for the successful cooperation of a group of operators that collaborate on controlling the robot action [16]. This phenomenon can also be significant for designing robots, when it is necessary to ensure the consistency of performing the robot functions, especially when designing a user interface in which participates more people.

### **General Approach for the Reduction of Causes of Errors in the Human - Robot System**

Given the large number of factors affecting the human-robot system, including the imperfection of the components of this system itself, it can be considered that the complete elimination of errors is impossible, that is, it is only possible to reduce their incidence frequency, as well as the consequences of the effects when an error already appears. Reduction of errors is based on predicting the possible errors and finding such solutions that will reduce and in certain situations prevent their occurrence.

In the case when defects that lead to the appearance of errors in an implemented human-robot system become apparent, a redesign procedure is applied, which can be an expensive and time-consuming process. With increasing frequency of errors occurrence, their detection and control are easier. When the errors are rare, then their detection is harder, and therefore their control.

#### **Basic solutions for reducing the personal errors**

There are two basic methods for reducing personal errors in the human-robot system. These are personal selection and training. The method of personal selection is based on the selection of the operator based on their abilities and skills required to perform the task, in accordance with the goal that the system should fulfill. On this occasion, the perceptual, intellectual and motor skills of the candidates are most often observed.

Appropriate operator training can also significantly reduce personal errors. However, there are several phenomena that are the occasional companion of each training. People can return to their old habits, or start using shortcuts or improper alternatives after some time after training. Also, over time, training instructions can be forgotten. In addition, the cost of additional training may be considerable.

#### **Basic solutions for reduction of errors in the design of the human - robot system**

In order for the robot design solution to be successful, it is necessary to further consider and anticipate the different possibilities for the occurrence of an error in the human - robot system, and then design such a solution that will prevent the occurrence of errors. Design solutions can contribute to the

reduction of those errors that primarily relate to the design of the robot itself, and then to the reduction of errors concerning the design of environmental conditions and the technological process itself (to a certain extent).

Although a robot is a component that alone can induce an error as a result of its inaccuracy or reduced reliability, when designing a robot, it is also necessary to bear in mind that the design of certain elements of a robot should support the characteristics and possibilities of the users, in order to prevent the occurrence of errors as a result of interaction with an operator. Different solutions aimed at reducing errors and lessening the consequences of these errors from the aspect of safety in the human-robot system have been presented in [5]. There are three basic design approaches aimed at preventing errors when interacting with a robot [3]:

1. Exclusion design is a design method that making of mistakes makes impossible.
2. Prevention design is a design method where making mistakes is difficult but not impossible.
3. The fail-safe design is a type of design solution that the consequences of an error are reduced, while it is not necessary that the solution necessarily diminishes the probability of an error. For example, for sensing errors, it becomes necessary to stop the task and make the necessary correction [13]. In this approach, an error can also be automatically compensated by activating additional mechanisms in the event of a malfunction or an error in the system.

#### **Basic solutions for reduction of errors that originate from the environmental conditions**

Certain intensive changes in working environment conditions, robot work in conditions outside the specified and predicted can lead to robot error. Additionally, the rapid and intensive changes of the working environment conditions, as well as the long-term impact of the working environment conditions versus the comfort, in the environment where works the operator who controls the work of the robot can also cause an error in the system.

Regarding the impact of the thermal expansion effect in relation to tasks requiring high precision, in order to reduce the errors of industrial robots, in Slamani,[14] it is recommended that the robot should be warmed up for several hours (after a cold start). Generally, in order to reduce the errors caused by working environment conditions, it is necessary to predict under what conditions the robot will perform tasks and design it for these conditions. In addition, it is necessary to monitor (measure) the environmental conditions in which the robot performs the task. If it is found that some of the environmental parameters are out of the limits that is provided by the design solution, it is necessary to provide the possibility of immediately stopping the work of the robot, in order to prevent the appearance of larger errors and the potentially greater damage.

The conditions in which the operator controls the work of robot should meet the ergonomic criteria. These conditions should also be measured and, if necessary, corrected. A special problem is controlling the work of robots in open space. In some cases, strong sunlight can reduce the visibility of the display by which the operator controls the state of the robot. Of course, there are also other environmental conditions that can interfere with the work of the operator in an open space. In order to reduce errors caused by environmental conditions, numerous design solutions can be applied, depending on the type of external factor that is the potential cause of the error. All these solutions should be designed in accordance with the ergonomic criteria and requirements. In the case when the operator's isolation from unfavorable environmental conditions is not possible, or when design solutions cannot be realized for various reasons (or do not give adequate results), the use of personal protective equipment is an option which in certain situations can give satisfactory results and lead to the reduction of errors.

#### **Basic solutions for reduction of errors from application of inadequate technological procedure**

As mentioned above, under the technological procedure here we mean the prescribed methodology of the functioning of the human - robot system that is formed in order to accomplish the task for which the system is intended. Timely replacement of robot parts due to their deteriorations is an example of a preventive solution within a technological procedure that is aimed at reducing errors in the H-R system. When it comes to modeling errors, in case a simplified geometric model is used, errors can be reduced by its replacement with a more precise model in the software application [13]. Choice of precise calibration equations will allow the reduction of calibration errors [10]. Appropriate calibration can also reduce sensing errors.

Two human - robot systems composed of components (humans and robots) of the same or approximately the same quality due to a different technological procedure can produce different results, which essentially reflects on the efficiency of these systems. Of particular importance is the study of those technological procedures that (in addition to their impact on efficiency) lead to the errors in work.

Globally, the basic solutions for reducing errors from the application of an inadequate technological procedure can be divided into two groups, depending on whether the technological procedure leading to the occurrence of errors is properly conceived or not. If the technological process that results in errors in the work is not properly conceived, then, in addition to its audit in a strictly procedural sense, it is also necessary its ergonomic verification, which is based on the application of numerous methods for detecting errors in the operator's work (eg time and motion study, in the case of application of robots in the realization of surgical operations). Such ergonomic analysis will contribute to the detection of errors related to the way in which the task is to be executed, as well as in the elimination of these errors.

If the technological procedure leading to errors in work is properly conceived, then it is necessary to control the written and oral procedures that are presented to the operator. In such situations, the possible source of errors are unclear or inaccurate instructions presented to the operator or user. The basic solution in such situations is redesigning the operating instructions in accordance with the ergonomic recommendations for the design of technical and project documentation.

### **Basic solutions for reducing errors that arise from interactions with other persons**

In relation to the observed human-robot system, the interaction of the operator with other persons can be manifested in two ways through the occurrence of errors. In the first case, other persons accidentally or intentionally (when it comes to abuse) transmit to the operator interacting with the robot the wrong information, which affects the implementation of the technological procedure. In the second case, other faces are a disturbing factor in terms of reducing the resources of attention related to the implementation of the technological process. In rare situations, when it comes to violence, other faces can represent a physical barrier that causes the occurrence of errors in work.

In the case of the possibility of transmitting the wrong information by another person, the basic solution is based on checking that information with the competent person, or checking of deviation of that information from the official information given in the form of written procedures. Other persons sometimes direct to the use of "easier procedures", which not only can violate the envisaged technological procedure, but lead to errors with the catastrophic outcome. In the case when other persons act as a disruptive factor, in addition to reducing attention when a user interacts with a robot, they may even cause mental stress (such as in the case of robot control in the field in order to disable a terrorist group) and thus significantly reduce an ability of the operator to work, which can further lead to the errors in the work. In such a situation, the most effective solution is to isolate the operator from such influences, to monitor and control persons acting as a disturbing factor, and to take appropriate measures to eliminate their effects.

### **Conclusion**

Since one error can have several causes, it can be classified into several categories of the presented model for classification of defects in the human-robot system. Finding the cause of the error in only one of the categories can be a possibly good partial solution. The complete solution implies looking for the cause of errors in all categories defined by the model presented in this paper.

Most designers when designing a robot are oriented primarily on only one component of the system - the robot. If a system is designed in which a human is involved in controlling the work of a robot, often the characteristics of an operator are included

in the designing process only at the intuitive level. Most other components that can affect the occurrence of an error in a human-robot system are often not considered at all or are being taken into account superficially. However, a good design of a human-robot system implies a comprehensive, multidisciplinary, systemic approach. It is necessary that experts from various profiles, including experts in the domain of human factor and ergonomics, are included in the designing process. It is desirable that the experts from those areas are involved in the design of a human-robot system yet in the phase of concept forming. They can also provide the necessary information for each stage of the designing process. Their experience is particularly pronounced when designing the control interface.

Therefore, only a comprehensive approach, which encompasses all possible causes that may lead to an error in the H - R system can contribute to reducing the errors in the human - robot system. Such an approach can have positive effects on the efficiency of the functioning of this system, as well as on improving its safety and general usability.

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