



The Review of Reliability Factors Related to Industrial Robots



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Abstract

Although, the problem of industrial robot reliability is closely related to machine reliability and is well known and described in the literature, it is also more complex and connected with safety requirements and specific robot related problems (near failure situations, human errors, software failures, calibration, singularity, etc.). Compared to the first robot generation, the modern robots are more advanced, functional and reliable. Some robot's producers declare very high robot working time without failures, but there are fewer publications about the real robot reliability and about occurring failures. Some surveys show that not every robot user has monitoring and collects data about robot failures. The practice show, that the most unreliable components are in the robot's equipment, including grippers, tools, sensors, wiring, which are often custom made for different purposes. The lifecycle of a typical industrial robot is about 10-15 years, because the key mechanical components (e.g. drives, gears, bearings) are wearing out. The key factor is the periodical maintenance following the manufacturer's recommendations. After that time, a refurbishment of the robot is possible, and it can work further, but there are also new and better robots from modern generation.

Keywords: Industrial robot; Reliability; Failures; Availability; Maintenance; Safety; MTTF; MTBF; MTTR; DTDTRF

Introduction

Nowadays, one can observe the increasing use of automation and robotization, which replaces human labor. New applications of industrial robots are widely used especially for repetitive and high precision tasks or monotonous activities demanding physical exertion (e.g. welding, handling). Industrial robots have mobility similar to human arms and can perform various complex actions like a human, but they do not get tired and bored. In addition, they have much greater reliability than human operators. The problem of industrial robot reliability is like machine reliability and is well known and described in the literature, but because of the complexity of robotic systems is also much more complex and is connected with safety requirements and specific robot related problems (near failure situations, hardware failures, software failures, singularity, human errors etc.). Safety is very important, because there were many accidents at work with robots involved, and some of them were deadly. Accidents were caused rather more often by human errors than by failures of the robots.

The research about robot reliability was started in 1974 by Engleberger, with publication, which is a summary of three million hours of work of the first industrial robots—Unimate[1]. A very comprehensive discussion over the topic is presented by Dhillon in the book, which covers the problems of robot reliability and safety, including mathematical modelling of robot reliability and

some examples[2]. An analysis of publications on robot reliability up to 2002 is available in Ref. Dhillon et al.[3], and some of the important newer publications on robot reliability and associated areas are listed in the book [4]. The modern approach to reliability and safety of the robotic system is presented in the book, which includes Robot Reliability Analysis Methods and Models for Performing Robot Reliability Studies and Robot Maintenance[5]. The reliability is strongly connected with safety and productivity, therefore other researches include the design methods of a safe cyber physical industrial robotic manipulator and safety-function design for the control system or simulation method for human and robot related performance and reliability[6-7]. There are fewer publications about the real robot reliability and about occurring failures [8]. The survey shows that only about 50 percent of robot users have monitoring and collect data about robot failures.

Failure analysis of approximately 200 mature robots in automated production lines, collected from automotive applications in the UK from 1999, is presented in the article, considering Pareto analysis of major failure modes. However, presented data did not reveal sufficiently fine detail of failure history to extract good estimates of the robot failure rate[9-10].

In the article 11. Sakai et al.[11], the results of research about robot reliability at Toyota factory are presented. The defects of 300

units of industrial robots in a car assembly line were analyzed, and a great improvement in reliability has been achieved. The authors consider as significant activities that have been driven by robot users who are involved in the management of the production line. Nowadays, robot manufacturers declare very high reliability of their robots [12]. The best reliability can be achieved by the robots with DELTA and SCARA configuration. This is connected with lower number of links and joints, compared to other articulated robots. Because each additional link with serial connection causes an increase of the unreliability factors, therefore, some components are connected parallel, especially in the Safety Related Part of the Control System (SRP/CS), which have doubled number of some elements, for example emergency stops. Robots are designed in such way that any single, reasonably foreseeable failure will not lead to the robot's hazardous motion [13]. Modern industrial robots are designed to be universal manipulating machines, which can have different sort of tools and equipment for specific types of work. However, the robot's equipment is often custom made and may turn out to be unreliable as presented in, therefore, the whole robotic system requires periodic maintenance, following to the manufacturer's recommendations [14-15].

operators and robots in cooperative tasks, therefore, the safety plays a key role. Safety can be transposed in terms of functional safety addressing the functional reliability in the design and implementation of devices and components that build the robotic system [16].

Robot Reliability

The reliability of objects such as machines or robots is defined as the probability that they will work correctly for a given time under defined working conditions. The general formula for obtaining robot reliability is [2]:

$$R_r(t) = \exp(-\int_0^t \lambda_r(t)dt) \dots\dots\dots (1)$$

Where:

$R_r(t)$ is the robot reliability at time t,

$\lambda_r(t)$ is the robot failure rate.

In practice, for description of reliability, in most cases the MTTF (Mean Time to Failure) parameter is used, which is the

expected value of exponentially distributed random variable with the failure rate λ_r [2].

$$MTTF = \int_0^\infty R_r(t)dt = \int_0^\infty e^{-\lambda_r t} dt = \frac{1}{\lambda_r} \dots\dots\dots (2)$$

In real industrial environments, the following formula can be used to estimate the average amount of productive robot time, before robot failure [2]:

$$MTTF = \frac{PHR - DTDTRF}{NRF} \dots\dots\dots (3)$$

Where:

PHR – is the production hours of a robot,

NRF – is the number of robot failures,

DTDTRF – is the downtime due to robot failure in hours,

MTTF – is the robot mean time to failure.

In the case of repairable objects, the MTBF (Mean Time Between Failures), and the MTTR (Mean Time to Repair) parameters, can be used.

$$MTBF = MTTF + MTTR \dots\dots\dots (4)$$

The reliability of the robotic system depends on the reliability of its components. The complete robotic workstation includes:

- A. Manipulation unit (robot arm),
- B. controller (computer with software),
- C. equipment (gripper, tools),
- D. workstation with workpieces and some obstacles in the robot working area,
- E. safety system (barriers, curtains, sensors),
- F. human operator (supervising, set up, teaching, maintenance).

The robot system consists of some subsystems that are serially connected (as in the Figure 1) and have interface for communication with the environment or teaching by the human operator. The robot arm can have different number of links and joints N. Typical articulated robots have N=5-6 joints as in the Figure 2, but more auxiliary axes are possible.

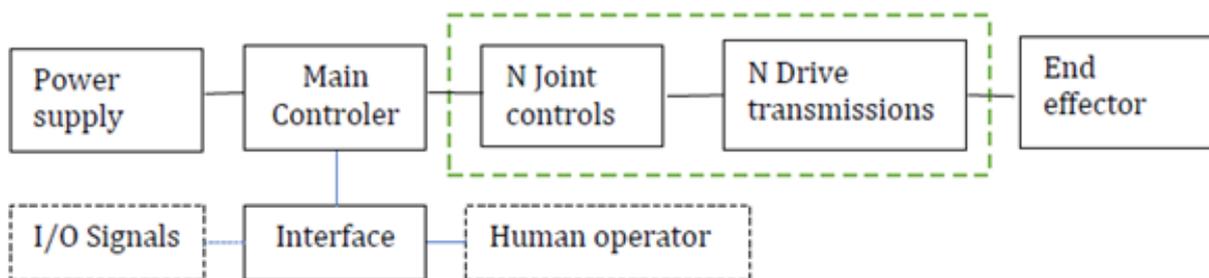


Figure 1: The schema of industrial robot's structure with main subsystems.

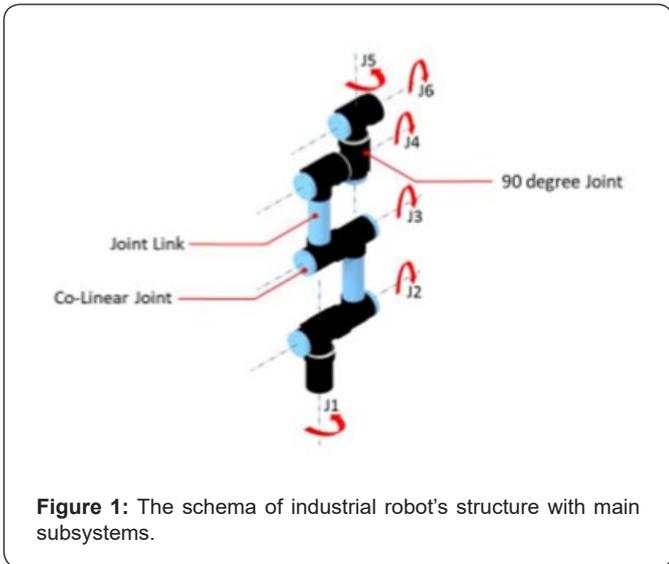


Figure 1: The schema of industrial robot's structure with main subsystems.

For serially connected subsystems, each failure of one component brings the whole system to fail. Considering complex systems, consisting of n serially linked objects, each of which has exponential failure times with rates $\lambda_i, i= 1, 2, \dots, n$, the resultant overall failure rate λ_s of the system is the sum of the failure rates of each element λ_i [2]:

$$\lambda_s = \sum_{i=1}^n \lambda_i \dots\dots\dots (5)$$

Moreover, the system MTBFS is the sum of inverse MTBF_{*p*} of linked objects:

$$\frac{1}{MTBF_s} = \sum_{i=1}^n \frac{1}{MTBF_i} \dots\dots\dots (6)$$

There are different types of failures possible:

- A. Internal hardware failures (mechanical unit, drive, gear),
- B. Internal software failures (control system),
- C. External component failures (equipment, sensors, wiring),
- D. Human related errors and failures that can be:
 - a. Dangerous for humans (e.g. unexpected robot movement),
 - b. Non-dangerous, fail-safe (robot unable to move).

Also possible are near failure situations and robot related problems, which require the robot to be

stopped and human intervention is needed (e.g. recalibration, reprogramming). Because machinery failures may cause severe disturbances in production processes, the availability of means of production plays an important role for insuring the flow of production. Inherent availability can be calculated with the formula 7 [2].

$$Availability = \frac{MTBF}{MTBF + MTTR} \dots\dots\dots (7)$$

For example, the availability of Unimate robots was about 98 % over the 10-years period with MTBF=500h and MTTR=8 hours [2].

The reliability of the first robot generation represents the typical bathtub curve (as in Figure3), with high rate of early "infant mortality" failures, the second part with a constant failure rate, known as random failures and the third part is an increasing failure rate, known as wear-out failures (it can be described with the Weibull distribution).

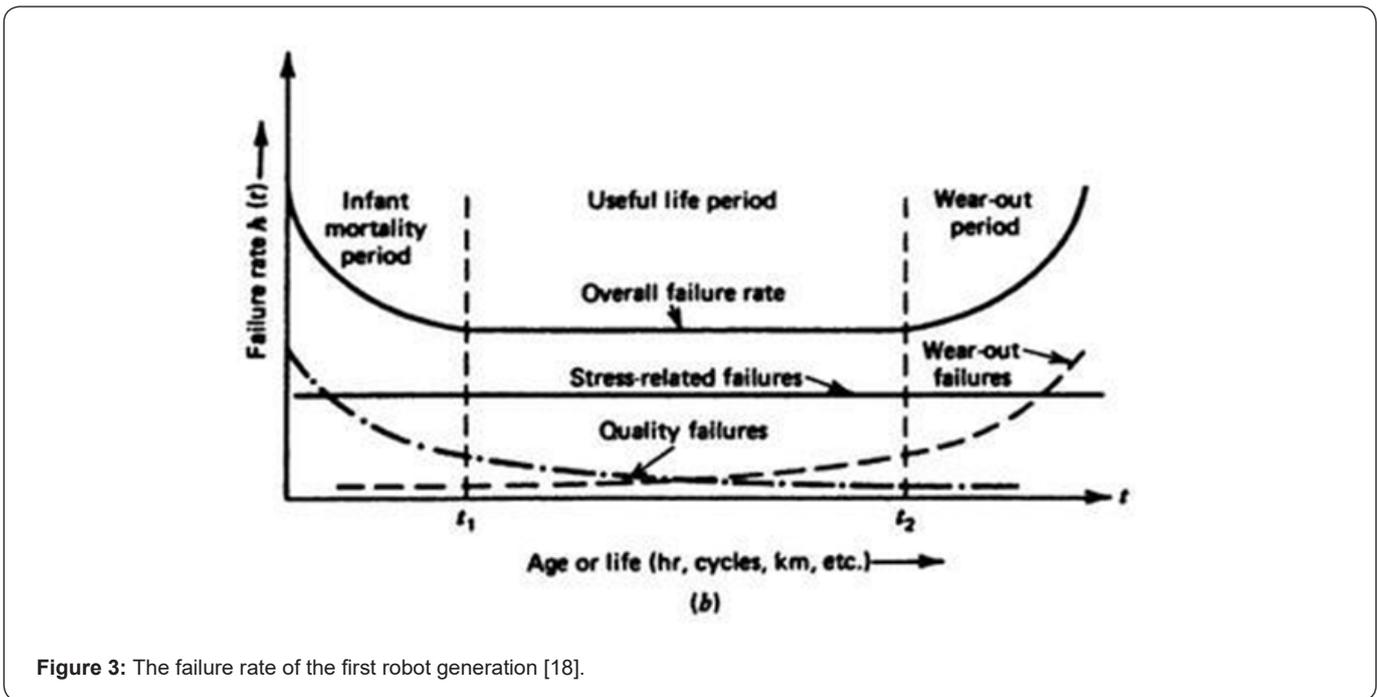


Figure 3: The failure rate of the first robot generation [18].

Therefore, the standard [17] was provided, in order to minimize testing requirements that will qualify a newly manufactured (or a newly rebuilt industrial robot) to be placed into use without additional testing. The purpose of this standard is to provide assurance, through testing, that infant mortality failures in industrial robots have been detected and corrected by the manufacturer at their facility prior to shipment to a user. Because of this standard, the next robot generation has achieved better reliability, without early failures, with MTBF about 8000 hours [16]. In the article Sakai & Amasaka [11], the results of research about robot reliability at Toyota are presented. Great improvement was achieved with an increase of the MTBF to about 30000 hours.

Nowadays, robot manufacturers declare an average of MTBF = 50,000 - 60,000 hours or 20 - 100 million cycles of work [12]. The best reliability is achieved by the robots with SCARA and DELTA configuration. This is connected with lower number of links and joints, compared to other articulated robots. Some interesting conclusions from the survey about industrial robots conducted in Canada in year 2000 are as follows [9]:

- A. Over 50 percent of the companies keep records of the robot reliability and safety data,
- B. In robotic systems, major sources of failure were software failure, human error and circuit board troubles from the users' point of view,
- C. Average production hours for the robots in the Canadian industries were less than 5,000 hours per year,
- D. The most common range of the experienced MTBF was 500–1000h (from the range 500-3000h)
- E. Most of the companies need about 1–4h for the MTTR of their robots (but also in many cases the time was greater than 10h or undefined).

The current industrial practice show that the most unreliable components are in the robot's equipment, including grippers, tools, sensors, wiring, which are often custom made for different purposes. This equipment can be easily repaired by the robot

user's repair department. But the failure of critical robot component requires intervention of the manufacturer service and can take much more time to repair (and can be counted in days). Therefore, for better performance and reliability of the robotic system, periodic maintenance is recommended.

Robot Maintenance

Three basic types of maintenance for robots used in industry are as follows [4]:

Preventive maintenance

This is basically concerned with servicing robot system components periodically (e.g. daily, yearly. ...)

Corrective maintenance

This is concerned with repairing the robot system whenever it breaks down.

Predictive maintenance

Nowadays, many robot systems are equipped with sophisticated electronic components and sensors; some of them are capable of being programmed to predict when a failure might happen and to alert the concerned maintenance personnel (e.g. self-diagnostic, singularity detection). Robot maintenance should be performed, following to the robot manufacturer's recommendations, which are summarized in the Table 1 [15]. Preventive maintenance should be provided before each automatic run, including self-diagnostic of the robot control system, visual inspection of cables and connectors, checking for oil leakage or abnormal signals like noise or vibrations. The replacement of the battery, which powers the robot's positional memory, is needed yearly. If the memory is lost, then remastering (recalibration, synchronization) is needed. Replenishing the robot with grease every recommended period is needed to prevent the mechanical components (like gears) from wearing out. Special greases are used for robots (e.g. Moly White RE No.00) or grease dedicated for specific application like for the food-industry. Every 3-5 years a fully technical review (overhaul) with replacement of filters, fans, connectors, seals, etc. is recommended.

Table 1: Robot maintenance procedures [4,15].

No	Maintenance Procedure	Time Period
1	Preventive maintenance–visual inspection, checking of abnormal signals, self-diagnostic of control system	daily
2	Periodic maintenance service–battery replacement	yearly
3	Overhaul–greasing, replacement of filters, fans, etc.	every 3÷5 years
4	Refurbishment–cleaning, replacement of defected or damaged components, e.g. bearings, brakes, gears, motors	after 10÷15 years

Performing daily inspection, periodic inspection, and maintenance can keep the performance of robots in a stable state for a long period. The lifecycle of typical robot is about 10-15 years, because the wear of key mechanical components (drives, gears, bearings, brakes) causes backlash and positional inaccuracy. After that time a refurbishment of the robot is possible, and it can

work further for long time. Refurbished Robots are also called re-manufactured, reconditioned, or rebuilt robots.

Conclusion

Nowadays modern industrial robots have achieved high reliability and functionality; therefore, they are widely used. This

is confirmed by more than one and half million of robots working worldwide. According to the probability theory, in such large robot population the failures of some robots are almost inevitable. The failures are random, and we cannot predict exactly where and when, they will take place. Therefore, the robot users should be prepared and should undertake appropriate maintenance procedures. This is important, because industrial robots can highly increase the productivity of manufacturing systems, compared to human labor; but every robot failure can cause severe disturbances in the production flow, therefore periodic maintenance is required, in order to prevent robot failures. High reliability is also important for the next generation of collaborative robots, which should work close to human workers, and safety must be guaranteed without barriers. Also, some sorts of service robots, which should help nonprofessional people (e.g. health care of disabled people) must have high reliability and safety. There have already been some accidents at work, with robots involved, therefore, the next generation of intelligent robots should be reliable enough to respect the Asimov's laws and do not hurt people, even if they make errors and give wrong orders.

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