# POLITECNICO DI TORINO

**Master's Degree in Mechatronic Engineering**

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# FMECA and FTA analysis for industrial and collaborative robots


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This work is dedicated to my family, in particular to my parents, Maurizio and Mariangela, for the continuous and essential support over the years, for the difficulties overcome and the sacrifices incurred in order to allow me to achieve this goal. Thank you

To my brother Michele, who has always been my greatest supporter and has always believed in me. Your encouragement has motivated me to move forward and improve myself

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# Abstract

In industrial manufacturing the automation of production processes has become a core factor and robots play a key role in improving productivity, availability and safety. In this prospective, unexpected robot downtime or failure may not only affect daily production tasks, but also cause unpredictable additional production and economic losses. Reliability and availability of the robots is therefore crucial in such systems and a careful maintenance based on condition monitoring of the actual operational health status of the machine has become to play a vital role in order to avoid unscheduled breakdowns, wasteful replacement or repairs before the end of the Remaining Useful Life (RUL) of components. In order to achieve better performances and reduce the overall maintenance costs, there has been an evolution in maintenance techniques: from the earliest Unplanned Breakdown Maintenance (UBM), which takes place only at breakdowns, passing through time-based Planned Preventive Maintenance (PPM), which sets a periodic interval to perform preventive maintenance prior to the Mean Time Between Failure (MTBF) regardless of the health status of a physical asset, finally settling on a more efficient maintenance approach which is Condition Based Maintenance (CBM). In order to perform CBM, an integration of health monitoring, diagnostics, prognostics and maintenance techniques (collectively known as Prognostics and Health Management (PHM)) is needed. In the current essay a Failure Mode, Effects and Criticality Analysis (FMECA) on the joint of a robotic manipulator (specifically UR5) is carried on, in order to find the most likely causes of fault/failure of the various components and a Fault Tree Analysis (FTA) is undertaken to find correlation between components faults.

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# Acronyms

**RIA** Robot Institute of America

**MTTR** Mean Time To Repair

**MTBF** Mean Time Between Failure

**UBM** Unplanned Breakdown Maintenance

**PSM** Planned Schedule Maintenance

**PPM** Planned Preventive Maintenance

**CBM** Condition Based Maintenance

**CNC** Computerized Numerical Control

**DOF** Degrees Of Freedom

**PHM** Prognostics and Health Management

**RUL** Remaining Useful Lifetime

**PBM** Physic Based Model

**FMECA** Failure Mode, Effects and Criticality Analysis

**FMEA** Failure Mode and Effects Analysis

**CA** Criticality Analysis

**RPN** Risk Priority Number

**WRPN** Weighted Risk Priority Number

**FTA** Fault Tree Analysis

**UMP** Unbalanced Magnetic Pull

**IEA** International Energy Agency

**ISO** International Organization for Standardization

**PMSM** Permanent Magnet Synchronous Motor

**HD** Harmonic Drive

**SWG** Strain Wave Gearing

**PCB** Printed Circuit Board

**IC** Integrated Circuit

**EMI** Electromagnetic Interference

**TLE** Top Level Event

**IMU** Inertial Measurement Unit

# Chapter 1

# Introduction

In recent years, with the continuous increase of raw materials, labour costs, and customer demand for products, industrial manufacturing has increasingly focused on the automation of production processes. Consequently, industrial robots started to play a decisive role in the overall automation of industrial manufacturing. Industrial robots have long been used in production systems in order to improve productivity, quality and safety in automated manufacturing processes [1].

The Robot Institute of America (RIA) has defined an industrial robot as a reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks [2].

The importance of robots to automation in manufacturing continues to grow and considering that manufacturing industry has been asking for greater robot accuracy and reliability, with improvement in both position and orientation, robots can be applied to a much broader range of applications that were once limited to custom machines, including high precision assembly, welding operations, two-sided drilling and fastening, material removal, automated fiber placement, industrial painting, and in-process inspection [3]. As robotic technologies become more integrated

with complex manufacturing environments, robot system reliability has become more critical. From the moment a robot system is put into service to enable a manufacturing process, the overall system, i.e. its constituent sub-systems and components, begin to degrade [4].
Take as an issue for example the study conducted in [5] which considered a typical automotive body production plant in which 200–300 robots are normally used. These may be engaged in a variety of applications such as spot and arc welding, component handling, painting and sealant application. The majority of robots work in series with others on a production line or on tandem lines [1], where they handle the movement of the parts between machines.

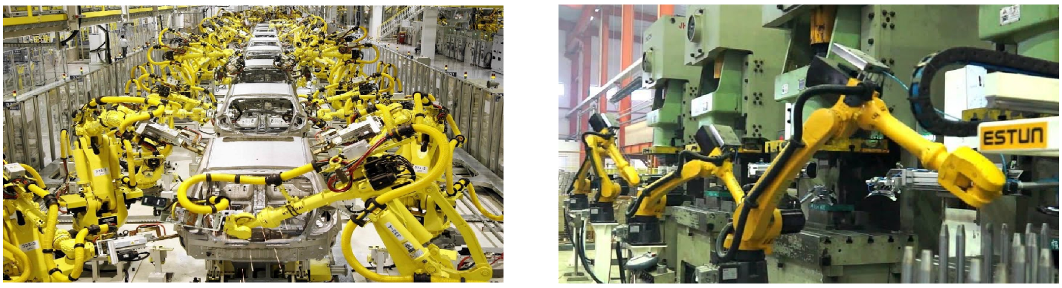


**Figure 1.1:** On the left: series production line [6]. On the right: tandem line [7]

A typical production line may consist of 20 robots, according to [5], each of which is critical to the operation of the line. This implies that any single robot failure may cause the entire line to fail. Similar critical scenarios occur in many other industries where the fault of individual robot components often causes chain reactions, resulting in the failure of the task process or even stoppage of the entire production system. Unexpected downtime and lost production are critical points for manufacturers, especially since they usually translate to financial losses.

[1]Tandem line: production line where the robotic manipulator is placed in between two machines and it is used to feed a machine and unload it, allowing to move the pieces from one processing machine to the next one.

Manufacturing companies focus their attention especially to degradation of the robotic system health rather than on the complete breakdown of the robot, which is the most critical scenario. As a matter of fact, a mild deterioration of the robot's positional health (position and orientation accuracy, ability to follow a predetermined trajectory), will have a negative impact on its performance. For example, an incipient fault, thus not necessarily a failure, can be enough to create production waste, since the degradation of the reliability can lead to a drop in manufacturing quality and production efficiency, especially for task that require high precision and trajectory accuracy such as spot welding, glue application, and so on. The robot, thanks to its advanced control algorithms, may be able to compensate for a fault, e.g. an increase in friction due to wear can be solved by providing a higher joint output torque by increasing the current supplied to the motor, therefore it is important to monitor parameters that may indicate abnormal behaviors (continuing this example: the current absorption by the joint motor) because in the long run, the product may no longer meet the required tolerances, creating a waste in the production chain, or the robot itself may experience a failure.

To avoid this undesirable scenario, the first solution adopted consisted in having available recovery stations that allow production to continue while diagnosis and repair of the failure proceeds, by provision of either a spare robot or a position where the work can be performed manually.

These measures have achieved plant availability at the expense of either additional plant equipment, which is usually idle, or by operating at reduced production rates during such periods.

However, the current trends in design of production lines is away from these measures for the following reasons, listed in [5]:

1. it is not cost effective to operate with a spare robot on the line;

2. it is not practical or cost effective to replace a defective robot on the spot;

3. the complexity of modern assembly demands that the variety of fixtures and end-effectors required makes each workstation unique;

4. substitution of a human operator has several shortcomings:

   (a) he cannot work as fast as a robot;

   (b) staff in automated plant are few;

   (c) he cannot be an expert in all the manufacturing operations.

The reliability and availability of the robots in such systems are critical. The study in question, conducted by *A. G. Starr et al.*, continues by asserting that early evidence suggested line availability of above 98%, though even with increasing unit availability this continues to be highly dependent on the Mean Time To Repair (MTTR)[2]. The failure rate for a series system is proportional to the number of units in the series; unavailability is cumulative. Modern robots achieve a high availability and reliability, but this leads to longevity (many robots in large plants have been in operation for over 10 years or more). The robotic system life cycles in most cases are based on supplier recommendation and usually span between 10 years to 15 years [8]. The recommended Mean Time Between Failure (MTBF)[3] as for Fanuc robots and ABB robots are 60,000 hours and 80,000 hours respectively based on continuous operation [8]. These robots, and the speed of their repair, become the weak link in system availability. Robot automated production lines are

[2]Mean Time To Repair (MTTR) is a basic measure of the maintainability of repairable items. It represents the average time required to repair a failed component or device.

[3]Mean Time Between Failures (MTBF) is the predicted elapsed time between inherent failures of a mechanical or electronic system, during normal system operation.

a high capital item, and it is expected that their programs, tooling and fixtures will be changed from one production model to the next one, while the transfer line and manipulators remain. It is important to minimize life cycle costs by extending the service life of mature robots. Hence, the policy for robot maintenance must be reviewed against these demanding performance measures.

## 1.1 Maintenance strategies

Three different maintenance strategies have been used since automation has played a key role in the manufacturing industry:

1. Unplanned Breakdown Maintenance (UBM);
2. Planned Preventive Maintenance (PPM);
3. Condition Based Maintenance (CBM).

A review of these maintenance strategies was made in [9] and it will be reported below.

### 1.1.1 Unplanned Breakdown Maintenance - UBM

Until the advent of CNC machines, and perhaps later, maintenance was largely unplanned: it took place when a breakdown occurred. However, the fact that the machine had a full time operator who was usually adept at recognizing the onset of a certain fault also supported the view that breakdown maintenance was adequate. There is no doubt that it was inefficient. The machine could be out of service at the most inconvenient times, there had to be larger inventories of work in progress in case of breakdown and a breakdown crew had to be always available. There was very little recording of breakdowns and consequently little evidence to the reliability of any machine. In conclusion, it is not good practice to allow complex plant to run to failure (breakdown maintenance (BM)) because:

1. consequential damage is expensive;
2. production is lost;
3. safety is compromised.

### 1.1.2 Planned Preventive Maintenance - PPM

The development of autonomous machines with the possibility of unmanned production certainly was one issue that caused a review of maintenance strategies. This led to Planned Preventive Maintenance (or Planned/Scheduled Maintenance). In this strategy the machine is operated until a predetermined (scheduled) time when maintenance is carried out. The aim is to prevent failure by timing maintenance to occur prior to an estimated life or Mean Time Between Failure (MTBF). In this model, as reported in [5], the probability density function of failure is assumed to correspond to the Gaussian distribution, and a high percentage of failures can be prevented if repair or replacement is effected prior to a fixed interval based on the standard deviation of the MTBF. This method follows strong assumptions that the machine is working under deterministic and static conditions [10], and therefore cannot be applied to system that operates in dynamic working regimes, like robotic manipulators. A working regime [11] refers to the working status of the machine under certain conditions and is often determined by several working regime parameters. Those can be distinguished into two categories:

1. operational parameters of machines such as speed and load;
2. working environmental parameters such as ambient temperature, humidity, and vibration.

Dynamic operating regimes are the conditions in which the working regime parameters are not fixed and can change over time. The robot-to-robot variations arise from the different working regimes among robots, for example the vibration conditions at different rotation speeds are different, and thus the degradation of components is different as well. Considering this situation, preventive maintenance may lead to untimely maintenance and non-optimal cost. This strategy has advantages (see Figure 1.2) in that it allows planning of maintenance resources, timing of downtime and replacement. Its main disadvantage lies upon the predetermined time between maintenance procedures. It is impossible to cater for all the varying failure patterns of machine elements and this, in general, leads to over-maintenance. It also leads to possibly unnecessary downtime of the machine and the oversupply of replacement elements at scheduled maintenance periods. Moreover, if the failures do not conform to a simple life model, or if insufficient data are available (which is usually the case), or even if a sporadic failure is considered, this policy is ineffective, resulting in a high level of unscheduled breakdowns and wasteful replacement or repair before the full life [5]. Planned schedule maintenance did bring along other useful developments in that much greater emphasis was laid upon the recording of element failure.

### 1.1.3 Condition Based Maintenance - CBM

Condition-based maintenance (CBM) initiates decisions and corrective actions on the detection of deterioration of monitored parameters in components or systems. CBM has been applied widely in the power, offshore and manufacturing industries, because it reduces the direct costs of maintenance, by cutting the number of unnecessary scheduled preventive maintenance operations, while avoiding the indirect costs of breakdowns, lost production and damage to plant [5]. CBM is a planned maintenance based upon measuring the condition of all machine elements during the normal operation of the machine. These measurements should allow the prediction of the time to failure for all elements avoiding unnecessary maintenance tasks by taking maintenance actions only when there is evidence of abnormal behaviours of a physical asset. It should allow maintenance to be planned before any elements fail. This is the state-of-the-art in machine maintenance [9]. A CBM program consists of three key steps, that are reported in [12] as:

1. data acquisition step (information collecting), to obtain data relevant to system health;

2. data processing step (information handling), to handle and analyse the data or signals collected in step 1 for better understanding and interpretation of the data;

3. maintenance decision-making step (decision-making), to recommend efficient maintenance policies. Diagnostics and prognostics (which will be defined in section 1.2.2) are two important aspects in a CBM program.

One great difficulty is the prediction of the failure of on-off type [9] (see hard faults in section 1.2.1) elements, which do not produce signals which degenerate with time. Figure 1.2 again shows the advantages and disadvantages of condition based maintenance. If developed properly it offers the best hope of the efficient use of complex and costly machines. On the other hand CBM is the most complex strategy among the three since a thorough knowledge of the system is required and the prognostic task adds a level of difficulty.

A summary of the main advantages and disadvantages of each maintenance strategy is shown in Fig. 1.2.

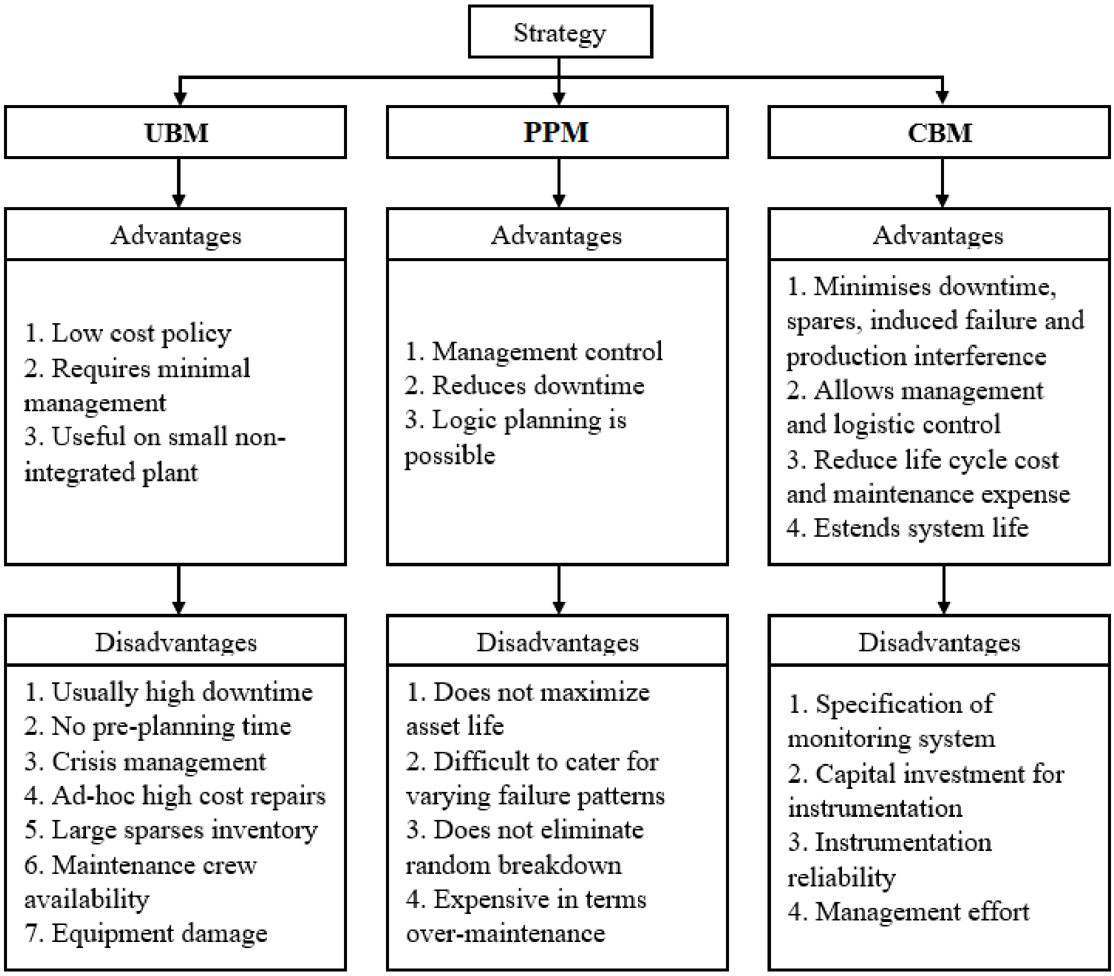


**Figure 1.2:** The effectiveness of different types of maintenance [9]

## 1.2 Prognostics and Health Management (PHM)

In order to minimize unexpected downtime and lost production, reduce maintenance costs and manage business risks while increasing asset reliability, availability and safety, manufacturers are developing new health monitoring, diagnostics, prognostics, and maintenance (collectively known as Prognostics and Health Management (PHM)) techniques. The purpose of PHM is to supervise and predict,on the base of processing data from the system, the future degradation of operating conditions, possibly managing maintenance based on the health state of the component. It is for this reason that it is an integral part of the CBM [13–15].
Health management is the process of taking timely, appropriate maintenance actions and making accurate logistics decisions based on outputs from diagnostics and prognostics, available resources and operational demand. It focuses on assessing impact of failures, and minimizing downtime and loss with maintenance management [10].

The maintenance strategies analysis made in the previous paragraph (Sec. 1.1) suggests that the incorporation of PHM to the condition based maintenance plan would be beneficial. However, the established condition monitoring techniques such as vibration, thermal, lubricant and noise levels analysis that are available for conventional (mainly rotating) machinery may be inappropriate for robots because of the nature of their operation and their complex structure [5].
Indeed, the following problems arise:

- the machine does not operate continuously, so it is difficult to obtain a consistent sample signal;

- failures are not restricted to a few known components. A robot system is complex, it contains robot arm, sensors, control systems, end-effectors, power supplies, and software all working together to perform a task. A fault of a component can cause a cascade fault of another one or errors can affect each other making it more difficult to determine the root cause;

- sensors mounted on robot in order to monitor its positional health (accelerometers, laser tracker-based systems, optical tracking systems) are expensive, and for example laser based systems need to maintain line-of-sight between the tracker and the target;

- failures of data collecting systems must be taken into account: drift of amplifier circuit, Signal-to-Noise Ratio (SNR) of system, characteristics of interchannel transfer function, quantization error of A/D converter, and various kinds of errors aroused by electromagnetic disturbance;

- the machine moves considerably when operating, so instrumentation fixed on axes (accelerometers, force/toque sensors, cameras, etc.), other than the first one, must move with the robot, but it must not obstruct movement whether on or off the robot;

- the machine has many axes which require individual instrumentation for certain monitoring techniques; e.g. vibration transducers must be located close to the bearings of interest.

In the case of robots, however, the principal mode of failure, i.e. positional error, may be caused by one or more of a large number of individual faults, since for a 6-DoF robot arm any component in any of the joint can be the triggering cause of failure. The continuing use of the maturing robot population, e.g. the decision whether to use the same robots for the next model of automobile, requires the operator to be convinced of machine health. It was shown that robots contribute up to 20% of the downtime on highly automated production lines. Up to 45% of that downtime is caused by inaccuracy in the robot positioning [5]. The robots are a significant factor in reducing plant availability so a way to assure a satisfactory level of reliability during the useful life of a physical asset is needed.

The objective of PHM is to provide an overview of the overall health state of the machine or complex system, to detect incipient component or system fault, perform failure diagnostics, failure prognostics, health management, assess the Remaining Useful Lifetime (RUL[4]) of the faulty component and assists in making correct decisions on machine maintenance. The PHM strategy optimizes the trade-off between costs and system efficiency, fully exploiting the useful life of the machine and, consequently, scheduling the maintenance activities in order to guarantee the maximum system capacity. Diagnostics and prognostics are the two main ingredients when performing PHM and in order to define them, a distinction between fault and failure has to be done first.

### 1.2.1 Fault versus Failure

**Fault**: is the earliest stage of a condition change, a physical or operational indication of abnormality in the system, when it is just beginning to come into being or become apparent, that will ultimately progress to functional failure [16]. When a fault occurs, the component is still operational but with a non-nominal behavior.
**Failure**: is an unexpected behavior, deviation from the normal behaviors with negative effects to the system, major plan breakdowns, substantial material damage, or complete breakdown/end of life of the component with consequent inability to perform the required function according to its specification [16]. A failure is usually the evolution of fault.

#### Hard and soft faults

It is useful here to distinguish between two different types of fault: soft and hard faults, described in [9]. Thir difference is shown in Fig. 1.3.

[4]Remaining Useful Life (RUL) is the operating time between fault detection and an unacceptable level of degradation.

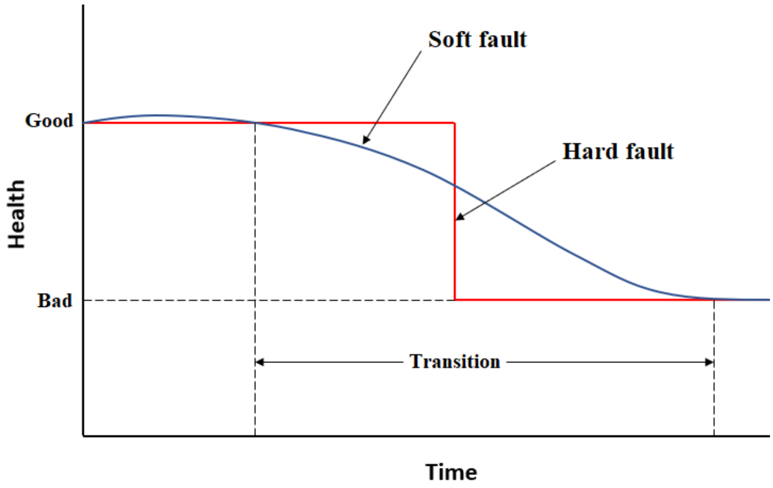


**Figure 1.3:** Hard and Soft faults [9]

The **soft fault** develops gradually with time. This is characteristic of many mechanical elements where wear takes place causing a gradual degradation of the operation of the element. Especially in the early stages of a disturbance, these faults will not result in a failure or malfunction since the control algorithms are sophisticated enough to handle changes in measurement and control values.

The **hard fault** takes place instantaneously: the element is either on or off. This is a characteristic of many electrical circuit elements, but does occur in mechanical elements when there is some type of catastrophic failure.
The difference between these faults is of primary importance. The soft fault leads to a predictable situation and consequently to condition monitoring and prognostics. The hard fault is generally unpredictable, but little research has been carried out in this area. There is a view that hard faults must exhibit some changes before the occurrence of the failure. For example, an electric fuse wire is sometimes quoted as an element which typically suffers a hard fault. However, it is quite probable, before the fuse burns out, that the dimensions of the fuse wire or perhaps its electrical resistance will change [9, 17] (but in order to monitor these signals, a sensor with high acquisition frequency will be needed). Hard faults, because they

lead to definite failure, lend themselves to easier diagnostics, but much harder prognostics.

### 1.2.2 Diagnostics and Prognostics

The objective of machine health management is to diagnose a fault (incipient failure) as early as possible and to prognose the remaining useful lifetime of the faulty component. Thus in the PHM approach, diagnostics and prognostics are the two major operations and a deeper analysis is needed.

**Diagnostics** deals with fault detection, isolation and identification when it occurs. Fault detection is a task to indicate whether something is going wrong in the monitored system; fault isolation is a task to locate the component that is faulty; and fault identification is a task to determine the nature, root causes, of the fault when it is detected [12]. In other word, diagnostics is a reactive process for maintenance decisions and cannot prevent downtime as well as corresponding expense from happening. In order to reduce maintenance cost and keep machine uptime at the highest possible level, maintenance should be carried out in a proactive way [10].

**Prognostics** deals with fault prediction before it occurs. Fault prediction is a task to determine whether a fault is impending and estimate how soon and how likely a fault will occur given the current machine condition and past operation profile [12]. The time left before observing a failure is usually called Remaining Useful Life (RUL) of component. While diagnostics is posterior event analysis, prognostics is prior event analysis. As [10] highlights, time is thus a critical variable in prognostics, distinguishing it from diagnostics where the emphasis is placed more on determining the causes of an already occurring fault or failure. Diagnostics, however, is required when fault prediction of prognostics fails and a failure occurs.

Obviously, prognostics is superior to diagnostics in the sense that prognostics can prevent faults or failures in order to be ready (with prepared spare parts and planned human resources) for the problems, and thus save extra unplanned maintenance cost, achieving zero-downtime performance. The RUL of each monitored component can be used to plan maintenance of the unit in advance of the failure, thereby having a significant impact on subsequent operations [18]. Nevertheless, prognostics cannot completely replace diagnostics since in practice there are always some faults and failures which are not predictable. Besides, prognostics, like any other prediction techniques, cannot be 100% sure to predict faults and failures. In the case of unsuccessful prediction, diagnostics can be a complementary tool for providing maintenance decision support. In addition, diagnostics is also helpful in improving prognostics in the way that diagnostic information can be useful for collecting more accurate event data and hence building better CBM models for prognostics [12].

### 1.2.3 Modelling approach

Prognostics methods can be classified into two principal approaches: physic based models and data-driven models.

**Physic Based Models (PBMs)**, also known as **Model-based prognostics**, is a technically comprehensive modeling approach [19] that deals with the prediction of the RUL of critical physical components by using mathematical and physical models of the degradation phenomenon (crack by fatigue, wear, corrosion, etc). Physic-based techniques require a detailed and thorough understanding of the system. As manufacturing facilities become complex and highly sophisticated, they are characterized by highly nonlinear dynamics coupling a variety of physical phenomena, in the temporal and spatial domains, and this makes building a mathematical model a laborious and difficult task.

**Data-driven prognostics** aims at transforming the data provided by the sensors into relevant models (parametric or non-parametric) of the degradation behavior. A data-driven model is a black-box model that requires a large number of training data [16]. A major challenge is the impracticality to generate and record fault data. Such data are often caused by hardware failure, which can hardly be emulated (for instance, deliberate destruction does not reflect the effects of wear [20]), but it is also a combination of many different states, which cannot be exhaustively emulated. The weak point of these models is therefore the lack of data, since very little recording of data coming from machinery faults and failures has ever been done over the years. This lack of data is the major problem which makes it difficult to use machine learning algorithms to predict failures, as they require numerous fault data of various kinds to be used as training data-set. As previously said in Section 1, being a robot an high capital resource, it is expected to keep it in operation even after a production model or task change (for example the same robotic arm can be destined to machine a new piece and therefore its working trajectory may change in a planned manner). This brings to one of the main disadvantages of the data-driven approach for robotic application: most of the data collected during its previous working condition can no longer be used to monitor its health status [21].

However, all of these approaches have drawbacks. Simulations are merely approximations of the real system, and the more detailed the model, the more cumbersome the generation and the more computational expensive the evaluation. Yet, the performance of model-based fault detection depends on model accuracy. Besides, using models implicitly defines the detectable faults, even if no specific fault pattern is required. Only those errors influencing modeled relations can be detected [20]. E.g. if nothing but the relationship between desired Cartesian end-effector position and joint position is modeled, a gear slippage forcing the controller to increase the motor current will remain undetected until further damage is caused to the system.

### 1.2.4 Critical component identification

To develop an effective and robust diagnostics and prognostics system for machine condition monitoring, it is necessary to have a comprehensive understanding of the component degradation behaviors and mechanisms under different load or environmental conditions. As previously mentioned, building an accurate mathematical model of a complex system like a robot is a demanding operation, thus the identification of the most critical components becomes a crucial aspect that allows to build a more efficient model. This is the main intent of this research: collect relevant information about the most common faults and failure modes of a robotic manipulator, which will help in building an accurate High Fidelity robot model.

Failure modes and causes must be investigated to better perform diagnostics and prognostics. Failure Mode, Effects and Criticality Analysis (FMECA) is an efficient tool used to analyze component failures, identify the main causes or mechanisms and failure effects on the system and/or component operation, considering criticality as an essential parameter. Through an in-depth FMECA procedure it is possible to understand which components are the most precarious and which failure modes are the most common. In this way it is doable to facilitate the creation of a physical model to simulate the evolution and the effects of the most critical faults and failures on the system. A detailed FMECA will be developed in the following chapter, Chap.3.

Identifying critical components is the major step in developing a PHM system. The goal of this procedure is to understand which components have the most significant impact on a system in terms of performance and/or cost of downtime.

A powerful method for identifying critical components is described in [10] where a four quadrant chart, as shown in Fig. 1.4, was used to display the frequency of failure versus the average downtime associated with failure for relevant components.

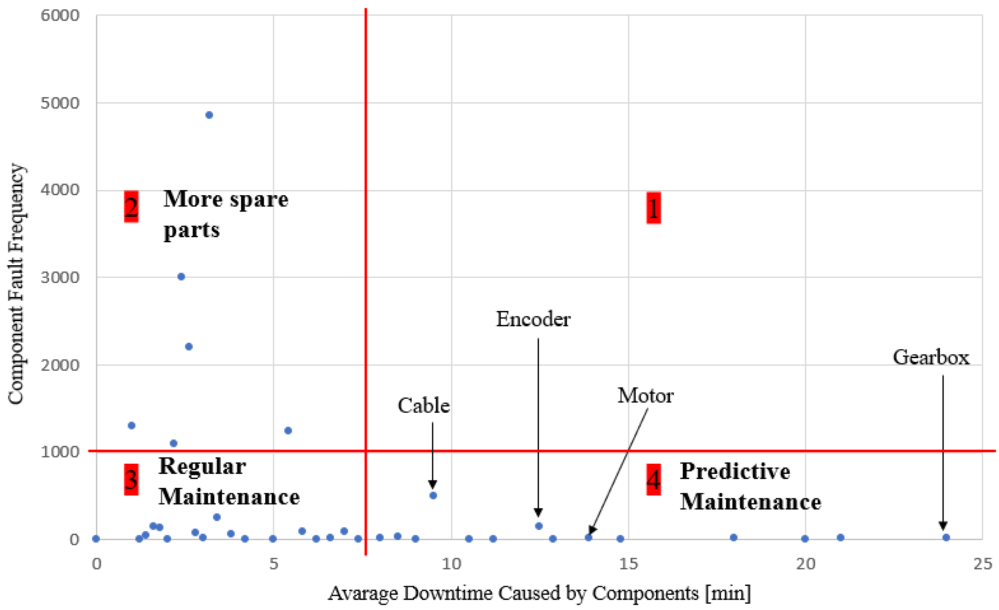


**Figure 1.4:** Four quadrant chart for identifying critical components [10]

- Quadrant 1 contains the components that not only fail most frequently, but whose failure also results in extensive downtime. Typically, there should not be any components in this quadrant because such issues should have been noticed and fixed during the design stage.

- Quadrant 2 contains components with a high frequency of failure, but short downtime for each component. The maintenance recommendation for such components is to have an adequate number of spare parts on hand.

- Quadrant 3 contains components with a low frequency of failure and low average duration of downtime per failure, which means that the current maintenance practices are working for these components and no changes are required.

- In Quadrant 4 lie the most critical components as their failures, though infrequent, cause the most downtime per occurrence. For such components, prognostics should be employed. An example is shown in Fig. 1.4, which indicates, for this specific situation, that cable, encoder, motor and gearbox are critical components on which prognostics should be focused.

It is relevant to notice the most of the joint components analyzed hereafter in this work belong to the $4^{th}$ quadrant.

# Chapter 2

# FMECA: Failure Mode, Effects and Criticality Analysis

Failure Mode, Effects and Criticality Analysis (FMECA) is one of the most widely used reliability evaluation/design technique which investigates the potential failure modes within a system and its equipment, in order to determine the effects and the severity upon components and system performance/status [22]. Its main objective is the identification of all possible failure modes and the classification of them according to their severity, frequency of occurrence and detectability. For a better comprehension of this document, it is important to give some definitions of FMECA related terms. According to the MIL-STD-1629A [23]:

- **failure cause**: the physical or chemical processes, design defects, quality defects, part misapplication, or other processes which are the basic reason for failure or which initiate the physical process by which deterioration proceeds to failure;

- **failure effect**: the consequence(s) a failure mode has on the operation, function, or status of an item;
- **failure mode**: the manner by which a failure is observed. Generally describes the way the failure occurs and its impact on equipment operation;
- **criticality**: a relative measure of the consequences of a failure mode and its frequency of occurrence;
- **severity**: the consequences of a failure mode. Severity considers the worst potential consequence of a failure, determined by the degree of injury, property damage, or system damage that could ultimately occur.

The FMECA can be divided into two procedures:

1. Failure Mode and Effects Analysis (FMEA);
2. Criticality Analysis (CA).

## 2.1 FMEA

Failure Mode and Effects Analysis (FMEA) is a procedure which covers identification of each potential failure mode of the system in order to determine the effects on performance and safety and to classify each potential failure mode according to its severity. The FMEA is initiated as an integral part of early design process of system functional assemblies because initially, hardware components may not be uniquely identified yet, but the functions of the system are already known. The procedure will provide quick visibility of the most obvious failure modes and identify potential single failure points, some of which can be eliminated with minimal design effort [24].

Nevertheless there are two primary approaches for accomplishing an FMEA:

- **functional approach**: recognizes that every item is designed to perform a number of functions that can be classified as outputs;

- **hardware approach**: lists individual hardware items and analyzes their possible failure modes.

It is important to keep in mind that each single component failure, as its effects are analyzed, is to be considered the only failure in the system. Where a single item failure is non-detectable, the analysis shall be extended to determine the effects of a second failure, which, in combination with the first undetectable failure, could result in a catastrophic or critical failure condition [23].
In summary, the following discrete steps shall be used while performing an FMEA:

1. define the system to be analyzed;

2. identify all potential item and interface failure modes and define their effects on the immediate function, on the system, and on the operation to be performed;

3. evaluate each failure mode in terms of the worst potential consequences which may result and assign a severity classification category.

### 2.1.1 Severity classification

Severity classifications are assigned to provide a qualitative measure of the worst potential consequences resulting from design error or item failure. It is an assessment of the impact of the failure mode effects on item operation, environment and safety. A severity classification shall be assigned to each identified failure mode and each item analyzed.
The following classification, shown in Table 2.1, is taken from [25].

| Category | Severity level | Consequences to people or environment |
|---|---|---|
| IV | Catastrophic | Failure of the system's primary functions with serious damages to the system/environment and/or personnel injuries. |
| III | Critical | Failure of the system's primary functions with considerable damage to the system/environment, but without serious threat to life or injuries. |
| II | Marginal | Degradation of system performance function(s) without appreciable damage to system or threat to life or injuries. |
| I | Insignificant | Degradation of the system's functions with no damage to the system and no threat to life or injuries. |

**Table 2.1:** Severity classification [25]

## 2.2 Criticality Analysis (CA)

Criticality analysis (CA) is a procedure by which each potential failure mode is ranked according to the combined influence of severity classification (collected through the FMEA) and probability of occurrence. CA adds a quantitative measure of the entity of a failure mode identified in the FMEA. Criticality gives a measure of the importance of a failure mode that would demand it to be addressed and mitigated. Its main function is to allow making a decision by prioritizing.

Probability of occurrence levels are defined according to [23] as follows:

**Level A - Frequent**: a high probability of occurrence during the item operating time interval. High probability may be defined as a single failure mode probability greater than 0.2 of the overall probability of failure during the item operating time interval.

**Level B - Probable**: a moderate probability of occurrence during the item operating time interval. Probable may be defined as a single failure mode probability of occurrence which is more than 0.1 but less than 0.2 of the overall probability of failure during the item operating time.

**Level C - Possible**: an occasional probability of occurrence during item operating time interval. Possible probability may be defined as a single failure mode probability of occurrence which is more than 0.01 but less than 0.1 of the overall probability of failure during the item operating time.

**Level D - Rare**: an unlikely probability of occurrence during item operating time interval. Rare probability may be defined as a single failure mode probability of occurrence which is more than 0.001 but less than 0.01 of the overall probability of failure during the item operating time.

**Level E - Remote**: a failure whose probability of occurrence is essentially zero during item operating time interval. Remote, or extremely unlikely, may be defined as a single failure mode probability of occurrence which is less than 0.001 of the overall probability of failure during the item operating time.

These classifications are collected in table format in the following Tab. 2.2.

| *Level probability of failure* | *Description* | *Analysis* |
|---|---|---|
| *A* | Frequent failure. The probability of failure exceeds 0.2 | In-depth quantitative analysis of criticality is required |
| *B* | Probable failure. The probability of failure from 0.1 to 0.2 | Quantitative analysis of criticality is desirable |
| *C* | Possible failure. The probability of failure from 0.01 to 0.1 | Only qualitative analysis is required |
| *D* | Rare failure. The probability of failure is from 0.001 to 0.01 | Analysis is not required |
| *E* | Remote failure. The probability of failure during a given time is below 0.001 | Analysis is not required |

**Table 2.2:** Probability of occurrence classification [25]

The CA is most valuable for maintenance and logistic support oriented analyses since failure modes which have a high probability of occurrence (high criticality numbers) require investigation to identify changes which will reduce the potential impact on the maintenance and logistic support requirements for the system [24].

Each potential failure is ranked by the severity of its effect and probability of its occurrence so that appropriate corrective actions may be taken to eliminate or control high risk components.

### 2.2.1 Risk Priority Number (RPN)

One of the methods for quantitative determination of criticality is the Risk Priority Number (RPN). The analysis of a system to obtain the RPN is an opinion-based technique where subjectivity is involved in assigning the scores for Severity (S), Occurrence (O) and Detectability (D). Risk is here evaluated by a subjective measure of the severity of the effect and an estimate of the expected probability of failure occurrence.
The common form of the risk priority number is defined in [26] as the product of the three ratings S, O and D:

$$RPN = S \times O \times D \tag{2.1}$$

where:

**S** = **Severity**, meaning an estimate of how strongly the effects of the failure will affect the system or the user;

**O** = **Occurrence** probability: denotes probability of occurrence of a failure mode for a predetermined or stated time period. It is a classification on the basis of Mean Time Between Failure (MTBF) ranges (e.g. likely, probable, occasional, unlikely);

**D** = **Detectability**: it indicates whether symptoms or indicators of a particular failure mode can be tracked via conventional or PHM sensors. This number is usually ranked in reverse order from the severity or occurrence number: the higher the detection number, the less probable the detection is. The lower probability of detection consequently leads to a higher RPN, and a higher priority for resolution of the failure mode.

**Negative aspects of RPN**

The range of the RPN values depends on the measurement scales for the three parameters, which usually use ordinal rating scales of 1 to 10, producing overall RPN values ranging from 1 to 1000.
The Risk Priority Number may then be used for prioritization in dealing with the treatment of failure modes. The failure modes are ordered with respect to their RPN and higher priority is usually assigned to a higher RPN. In addition to the magnitude of the risk priority number, the decision for mitigation is primarily influenced by the severity of the failure mode, meaning that if there are failure modes with similar or identical RPN, the failure modes that are to be addressed first are those with the higher severity ratings.
This is a limitation of this method, in fact, situations may occur in which a high severity failure mode turns out to have an overall RPN value much lower than an average level failure mode. This can be seen in the following example: a failure mode, $F_1$, with high severity, low rate of occurrence and very high detection, therefore:

$$S_1 = 10, O_1 = 3, D_1 = 2 \implies RPN_1 = 60; \tag{2.2}$$

has a much lower RPN than a second failure mode, $F_2$, with average parameter values:

$$S_2 = 5, O_2 = 5, D_2 = 5 \implies RPN_2 = 125; \tag{2.3}$$

Some other weaknesses about the RPN are that its scale is not continuous: there are cases in which the same RPN is obtained for different parameters value. For instance, if the following values are considered:

$$S_1 = 10, O_1 = 1, D_1 = 2 \implies RPN_1 = 20. \tag{2.4}$$

The same RPN is obtained with these other parameters:

$$S_2 = 1, O_2 = 2, D_2 = 10 \implies RPN_2 = 20, \tag{2.5}$$

but obviously the first one is to be considered with more caution since it has higher severity rate.

Another weakness is the sensitivity to small changes: a small change in one factor has a much larger effect when the other factors are large than when they are small, for instance, if we have

$$8 \times 8 \times 2 = 128, \text{ and } 8 \times 8 \times 3 = 192,$$

we have a certain delta, which is 64, versus the change that we have for instance in the following case, where the delta is 4:

$$2 \times 2 \times 2 = 8, \text{ and } 2 \times 2 \times 3 = 12,$$

In both cases we have that the third factor changes from 2 to 3, but, as we can see, the difference in the final result, is much larger in the first case, than in the second one.

Therefore, often a specific procedure ensures that failure modes with high severity ranking (i.e. 8, 9 or 10) are treated first despite the values of other parameters. In that case, the priority is driven by the magnitude of severity, rather than RPN alone. These numbers are used to establish corrective action priorities, but because of the subjective judgement required to assign them, they should be used only as indicators of relative priorities.

## 2.3 FMECA: strengths and weaknesses

FMECA is a very versatile method, however it has its own strengths and weaknesses, therefore, it should be judiciously applied.
Among the **benefits** it is possible to recall:

- it provides a basis for identifying failure root causes and developing corrective actions;
- it identifies failures with an unacceptable or significant effects on system operation, and it facilitates the determination of failure modes which may seriously affect safety of operations;
- it helps in identifying the need for the design methods for reliability improvement, for instance redundancy, component selection and so on, in a cost effective manner by intervening early in the development programme;
- it provides a framework to evaluate the probability of failure of the system and the criticality analysis;
- it helps to address safety and product liability problem areas, or non-compliance with regulatory requirements, demonstrating that foreseeable risks have been identified and accounted for;
- it allows the development of an effective quality control, inspection and manufacturing process control;
- it assists maintenance strategy selection and provides a basis for planning a maintenance and support schedule, providing a final report valuable for giving evidence of the risk management process in the form of an easy to read table;
- predictive maintenance is an important factor for any industry to avoid the high cost of a breakdown. During the maintenance activity, different types of faults

need to be prioritized on the basis of their criticality. FMECA helps to prioritize different failures on the basis of RPN.

However, FMECA has some **weaknesses** as well:

- in general, FMECA is a method to analyze the effect of single failures, thus it is not effective in providing a measure of overall system reliability, even though it is a useful tool for supporting decision making. An analysis that takes into consideration the whole system in its complexity and interconnection between components is performed through the Fault Tree Analysis (FTA) which takes the outputs of the FMECA as inputs to evaluate the effects of the major failure modes on the entire system;

- it may be difficult and tedious when working on complex systems, because of the quantity of failure modes to consider, of detailed system information that needs to be examined, especially if, besides the complexity, we have a number of possible operating modes, repair and maintenance policies;

- one of the main assumptions of FMECA is the independence of failure modes. Therefore, it is not an effective method when representing relationships between multiple failure modes. This deficiency becomes even more pronounced in view of software/hardware interactions, where independence assumption does not apply. The interrelationship scenarios are better modelled using the approach of failure mode analysis with the FTA tool.

## 2.4 Case study: UR5

The industrial manipulator UR5, shown in Figure 2.1, has been chosen as case study of this research as it is the robot available in the university laboratory of the mechanical engineering department of Politecnico di Torino.

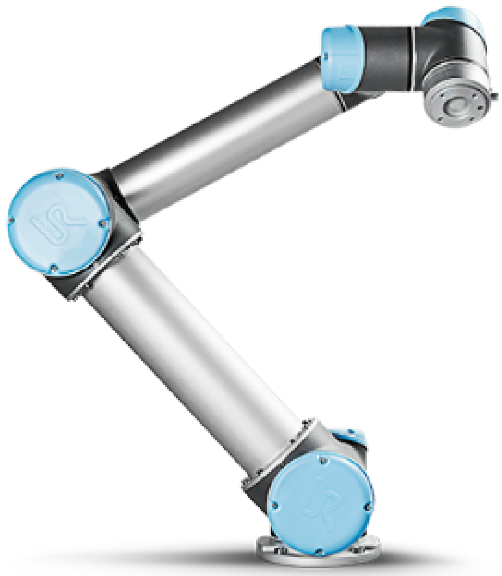

**Figure 2.1:** UR5 robot arm [27]

The UR5 is a collaborative robot, or cobot, member of the CB-series, developed by the Danish company Universal Robots. The UR family of collaborative robots offers four different payload options: 3, 5, 10 and 16 kg, corresponding to UR3, UR5, UR10 and UR16 [28]. As stated in [29], in order to be defined as "collaborative", the robotic system must be able to share the same workspace with the operator. This workspace is referred to as "collaborative workspace" [29], and it is shown in Fig. 2.2: a space within the operating space of the robot, where the cobot system (including the workpiece) and a human being can perform tasks concurrently during production operation.

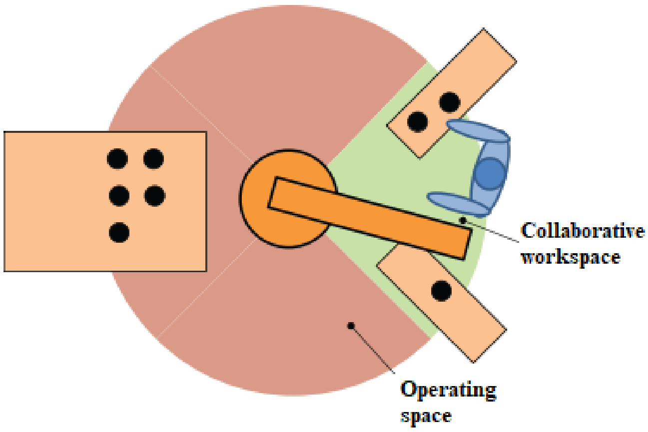


**Figure 2.2:** Collaborative workspace [29]

In such operations, the integrity of the safety-related control system is of major importance, particularly when process parameters such as speed and force are being controlled, since operators can work in close proximity to the robot system while power to the robot actuators is available, and physical contact between an operator and the robot system can occur within the collaborative workspace.
Thus a risk assessment analysis through FMECA and FTA is even more necessary to identify the hazards associated with a collaborative robot system application since in this case not only the quality of the product, but also the safety of the working personnel is endangered. Indeed, to achieve safety with respect to workers, robotic applications traditionally exclude operator access to the working area while the robot is active through protective barriers. According to the Danish company the key benefits of their robots are that they are light weight, safe and easy to use [28]. The system is considered safe because, in addition to not having any sharp edges in its links or joints, it implements the procedure of "protective stop" [30] which allows the robot to stop working as soon as it hits an obstacle sensed by a force/torque sensor in one of the joints. Moreover UR robots are equipped with special safety-related features, which are purposely designed to enable collaborative

operation, and are described as "safety configuration settings" in the next section, Sec. 2.4.1. Because of this, Universal Robots claims that their robots do not need a safety cage while operating together with a human being. By legislation, the UR company certifies the safety of the robot for collaborative applications, where "collaborative operation is only intended for non-hazardous applications, where the complete application, including tool/end effector, work piece, obstacles and other machines, is without any significant hazards according to the risk assessment of the specific application" [27], but this does not mean that safety analysis should not be carried out for every type of the robotic arm application. Considering this context, an analysis of possible failures that lead to non-nominal behavior becomes of fundamental importance.

### 2.4.1 UR5 specifications

Universal Robots UR5 is made up by three main parts: Control Box, where the motherboard and the safety control board are located, Teach Pendant, which is the interface between the operator and the robot, and the Robot Arm. In this research the effort will be focused on conducting an analysis on the robot arm, but it should not be forgotten that faults can be generated also from a software point of view, and safety-related features are purposely designed for collaborative robot applications. These features are configurable through the safety configuration settings [27] and consist in:

- force and power limiting;
- momentum (thus speed) limiting;
- TCP and tool/end-effector position limiting;
- TCP and tool/end-effector orientation limiting;
- boundaries in the cartesian space.

The UR5 has a rather standard layout for this kind of robotic arms: it is a 6-DoF anthropomorphic robot, with six revolute joints. It is composed of a main body, three revolute joints of which the first one is vertical and the other two are horizontal and parallel, and a non-spherical wrist, three more revolute joints with the axes not intersecting in a single point as shown in Figure 2.3.

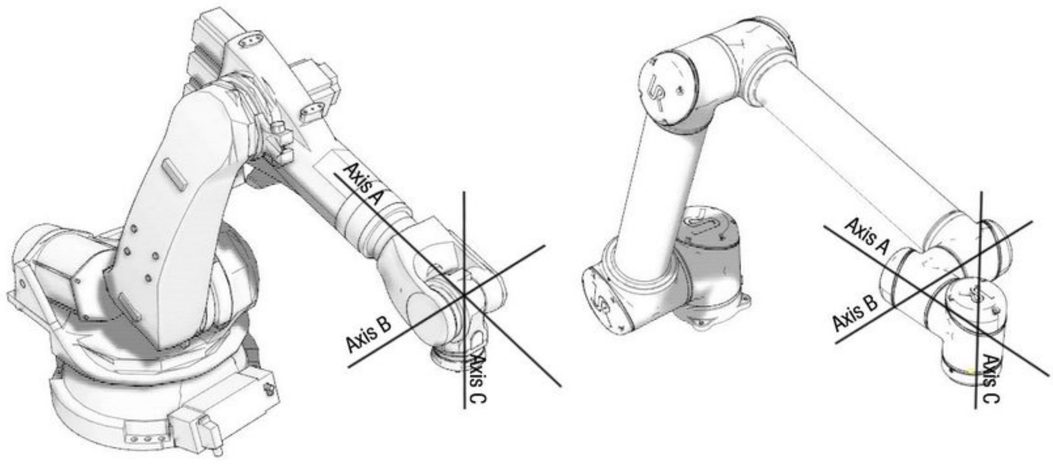


**Figure 2.3:** A spherical wrist on the left, a non-spherical wrist on the right [31]

The joints are represented in Fig. 2.4, and are named 0-Base, 1-Shoulder, 2-Elbow and 3,4,5-Wrist 1,2,3. The Base is where the robot is mounted, and at the other end (Wrist 3) the tool of the robot is attached. By coordinating the motion of each of the joints, the robot can move its tool around freely, with the exception of the area directly above and directly below the robot base, and of course limited by the reach of the robot (850mm from the center of the base) [27].

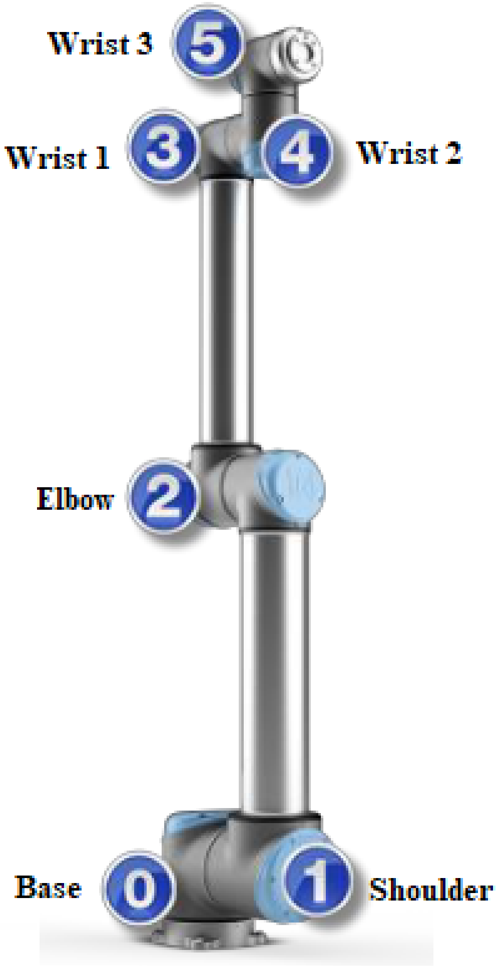


**Figure 2.4:** UR5: joints nomenclature [30]

In Table 2.3 the specifications given by Universal Robots in [27] are showed. One of the most important parameters for robotic applications is usually the repeatability and even though other comparable robots, in terms of size and payloads, achieve better performances (IRB1300 of ABB and the TX60 of Stäubli have a repeatability of 0.03 mm), a repeatability of 0.1 mm does not negatively affect diagnostics and prognostics studies on maintenance procedures with robots.

| **Technical specifications - UR5** | |
|---|---|
| Robot type | UR5 |
| Weight | 18.4 kg |
| Payload | 5 kg |
| Reach | 850 mm |
| Joint ranges | ± 360° on all joints |
| Joint max. speed | 180°/s |
| TCP max. speed | 1 m/s |
| Repeatability | ± 0.1 mm |
| Degrees of freedom | 6 rotating joints |
| I/O ports | 18 dig in, 18 dig out, 4 anl in, 2 anl out |
| I/O power supply | 24V 2A in control box and 12/24V 600mA in tool |
| Communication | TCP/IP, Ethernet socket & Modbus TCP |
| Programming | PolyScope graphical user interface |
| Noise | 72dB(A) |
| IP classification | IP54 |
| Power consumption | Approx. 200W using a typical program |
| Materials | Aluminium, PP plastic |
| Temperature | Working range of 0-50°C |
| Power supply | 100-240 VAC, 50-60 Hz |
| Calculated operating life | 35,000 hours |

**Table 2.3:** Technical specification of UR5 cobot arm [27]

By schematizing the structure of the robot, it can be seen that it is made up of a series of 6 joints connected together by rigid links, made of extruded aluminum tubes and plastic material. The simplicity of the structure lies in the fact that each joint has its own motor: there are not any transmission organs such as belts or gearboxes in between different joints and this is why link failure causes are not considered in the analysis that will be carried out in the following pages. Therefore it was decided to focus the study of this thesis on the analysis of the joint and its basic components, thus making the FMECA and FTA analysis valid for any type of robot, be it collaborative or industrial, as the main joint components are the same. As already specified in paragraph 2.4, for a collaborative robot this kind of analysis can be of added value as a fault or failure would be more critical, putting operator's health at risk.

## 2.5 UR5 safety considerations

According to safety standards every robot shall have a protective stop function and an independent emergency stop function. By definition from ISO 10218-1:2011 [32]:

- **protective stop**: is a type of interruption of operation that allows a cessation of motion for safeguarding purposes and which retains the programme logic to facilitate a restart;
- **emergency stop function**: is intended to avert arising or reduce existing hazards to persons, damage to machinery or to work in progress, and must be able to be initiated by a single human action.It removes power supply to the robot.

The differences between the two functions are summarized in the following table, Tab 2.4:

| **Parameter** | **Emergency stop** | **Protective stop** |
|---|---|---|
| Initiation | Manual | Manual, automatic or may be automatically initiated by a safety-related function |
| Reset | Manual only | Manual or automatic |
| Use frequency | Infrequent | Variable, from every operation to infrequent |
| Purpose | Emergency | Safeguarding or risk reduction |
| Effect | Remove energy sources to all hazards, the robot turns off | Safely control the safeguarded hazard(s), but the power supply of the robot is not turned off |

**Table 2.4:** Comparison of emergency and protective stops [32]

As can be seen Table 2.4, the main difference between the two types of stop lies in the fact that in the emergency stop the cobot is switched off, while in the protection stop program execution is suspended but the cobot remains on.
A previous research conducted at Politecnico di Torino, showed that the cobot, even if it identifies an anomalous behavior, and consequently implementing an automatic protective stop, it does not stop immediately, but has a stopping time that is a function of the payload, the arm extension and the movement speed. Therefore this information must be taken into consideration when analyzing the safety of the operator sharing the workspace the robot. Universal Robots makes available in [27] the stopping time (expressed in milliseconds) and the stopping distance (expressed in degrees) depending on the extension of the robotic arm and the load applied for base, shoulder and elbow joints, no information are available for wrist joints.

In the user manual of UR5 [27], Universal Robots warn to “not enter the safety range of the robot or touch the robot when the system is in operation". Yet it is also claimed that there is no need for safety shielding. This is because the arm will detect an impact larger than 200 N and will go into error mode. Still this will not guarantee that the robot is harmless, being specified on the user manual that “the robot force limitation does not give protection against momentum”. According to CORO [33] the maximal velocity of the TCP is 3 m/s instead of the 1 m/s stated in the specifications and they measured impact forces up to 1500 N (even though the tests were on steel-to-steel impact). On the other hand the tests were performed at a limited speed of 0.5 m/s, so this emphasizes that the UR5 can be potentially harmful.

## 2.6 Components of a robotic joint

As previously mentioned, it was decided to focus the attention of this study on the analysis of the robot joint as it constitutes the most complex element of the system, as well as the actuation organ of the robotic arm. Considering the joint, the individual components were then analyzed.

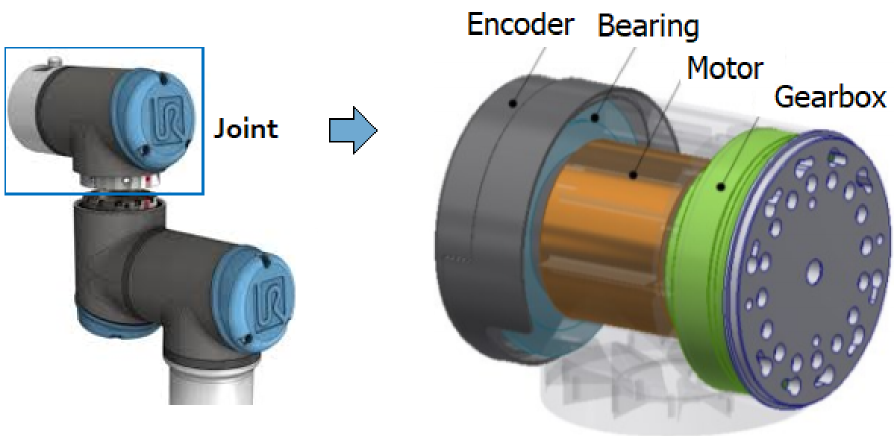


**Figure 2.5:** Robotic joint and its constituent components [30]

An in-depth analysis will be developed at the component level. The main components of a robotic joint are: electric motor, gearbox, encoders and bearings as highlighted in Figure 2.6.

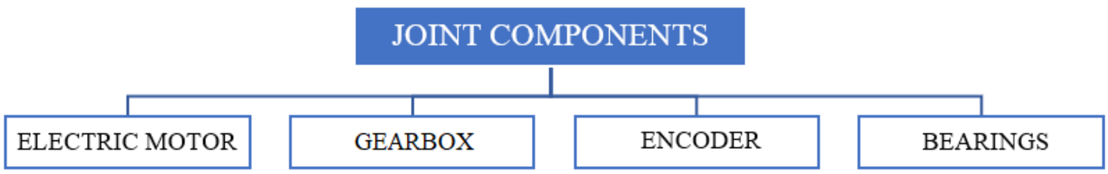


**Figure 2.6:** Components of a robotic joint

**Motors**: primary mechanisms by which robots move, converting the electrical energy that powers the robot into mechanical energy that allows the joint to rotate. In order to perform precise movements and achieve satisfactory level of accuracy a highly functional motor is needed, able to control position and speed of the robot. The UR5 mounts a KBM series permanent magnet AC brushless synchronous three-phase servomotor in each joint which is integrated directly into the housing of the robotic arm, using the latter to support the stator and reducer, thus eliminating the mechanical coupling components and consequently minimizing the weight and dimensions of the system.

**Gearbox**: in robotic applications, joint rotational speeds are much slower than the ones of motors. Gearboxes are used in this sense, to increase torque while reducing the speed. The output shaft of a gearbox rotates at a slower rate than the input shaft, and this reduction in speed produces a mechanical advantage, increasing torque. For this reason a gearbox with a transmission ratio of around 100 to 150:1 is mounted on each motor. In order to lighten the structure of the robot, while at the same time achieve high load capacity and torque amplification, the UR5 mounts an harmonic drive (SHG-2A Harmonic Drive ®) with reduction ratio of 101:1, which is preferred to classical serial or planetary gearboxes considered too heavy and less efficient.

**Figure 2.7:** SHG-2A-R Harmonic Drive [34]

**Encoder**: each joint of the UR5 is equipped with two AksIM™ magnetic rotary absolute encoders, which are non-contact high performance off-axis absolute rotary encoders designed for integration into space-constrained applications. The first encoder is attached to the reducer end to directly monitor the actual rotating angle of the robot joint and it is used for position control, while the second one is mounted before the motor to close the speed control loop. The encoder and the ring have been specifically designed in compact form for integration onto the reducer, and it increases the joint thickness by just 7 mm, as can be seen in Fig. 2.8.

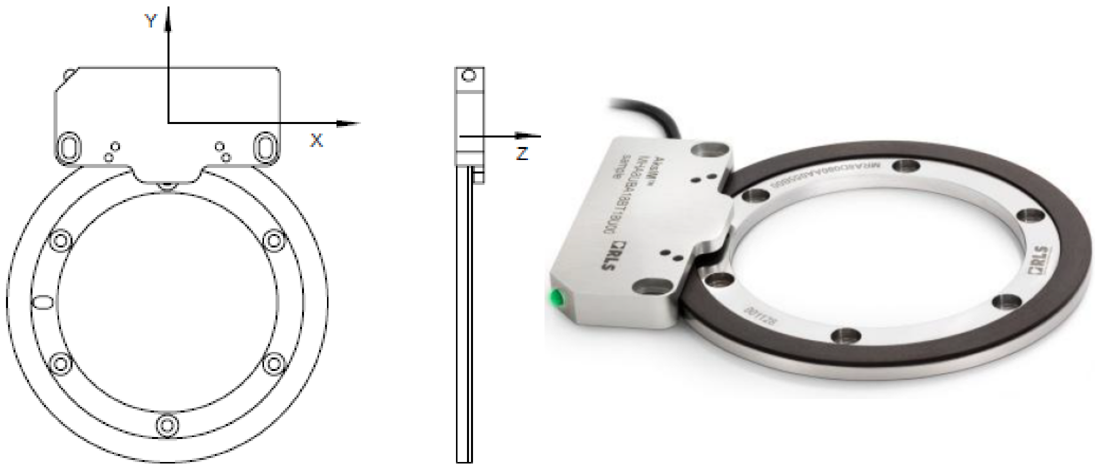


**Figure 2.8:** AksIM™ magnetic rotary absolute encoder mounted on UR5 [35]

**Bearings**: rolling bearings are fundamental components in any oscillating or rotating machine, providing support and guide, with minimal friction, and transferring loads between machine components. They allow to achieve high precision and low friction, enabling high rotational speed while reducing noise, heat, energy consumption and wear.
Each component introduced in this paragraph will then be studied in detail in the next chapter, Chap. 3, to investigate all the main causes of faults/failures, carrying out an FMECA analysis.

# Chapter 3

# FMECA on components of a robotic joint

As already said in Chapter 1, PHM allows to identify the presence of a defect before a failure occurs, to classify the detected fault, and to forecast its future evolution estimating the Remaining Useful Life. The fundamental principle for the implementation of PHM on a complex system concerns the understanding of the physical phenomenon behind the failure mechanism at component level, and the FMECA aims to achieve this goal. Indeed, as stated in chapter 2, the FMECA tries to correlate the failure events to their root causes (by identifying failure modes), their severity, frequency of occurrence and detectability. Of greatest interest would be the tracking of fault symptoms at early stages, which are monitored by sensors and monitoring equipment, in order to be able to act in a preventive manner.
In this chapter an in-depth analysis of each single component of the robotic joint will be carried out.

## 3.1 Procedure description

In order to properly perform the analysis, it is appropriate to report now the steps that will be carried out for each component, and the tables that will be used to assign the values to the parameters used to identify the RPN [36, 37], in the interest of avoiding repeating this step in each section. The FMECA analisys should be conducted following these steps, according to the instructions highlighted in [38]:

1. identify the purpose/objective of the system. Divide the system into a number of a subsystems such as components, parts or assemblies and define their objective;

2. identify the number of ways in which the fault/failure can occur for each subsystem, which will give the idea about the failure modes;

3. for each individual failure mode, identify its effects on the system, connected systems, process, connected processes, which indicate the potential effects of failure;

4. determine the severity of each effect, which is known as "severity rating" in traditional FMECA, which is indicated by S. The rating of the severity will vary from 1 to 10 in which 1 will indicate negligible and 10 will indicate catastrophic;

5. related to each failure mode, identify the root causes and list them in the FMECA table. For each cause define the occurrence rating, in the scale of 1 to 10, which is indicated by the symbol O in the traditional FMECA. In the occurrence rating, 1 will indicate remote and 10 will indicate the very high occurrence rate;

6. considering each failure mode, for detectability, indicated by D, assign 1 if

it can be easily detected, while 10 for the failure mode which is difficult to detect;

7. calculate the risk priority number which is the product of S, O and D. This will guide to rank the problems in order to decide the sequence in which they need to be addressed.

| **Effect** | **Description** | **Criteria: Severity of Effect on Product Manufacturing and Personnel** | **Rank** |
|---|---|---|---|
| Failure to meet safety and/or regulatory requirements | Extremely dangerous - no warning | May endanger machine or operator life without any prior warning. Total system breakdown | **10** |
| | Very dangerous - warning | May endanger machine or operator life with prior warning. Serious system disruption with interruption in manufacturing (line shutdown) | **9** |
| Major disruption | | Failure could cause moderate injury. 100% of products may have to be scrapped. Major disruption in operations | **8** |
| Significant disruption | Dangerous | Failure could cause minor injury. A portion of the production may have to be scrapped. Decrease line speed requiring major repairs/rework | **7** |
| Moderate disruption | Moderate danger | Failure could cause minor injury. Minor disruption in operations (production may require off line rework, some production waste) | **6** |
| | | Failure could cause very minor injury. A portion of the production may have to be reworked offline | **5** |
| Minor disruption | Low to moderate danger | Failure could cause very minor or no injury. Minor system problems that can be overcome with minor modifications to the system | **4** |
| | | Failure could cause no injury. Minor system problems that can be overcome with minor modifications to the system | **3** |
| Minimal disruption | Slight danger | Failure could cause no injury but the potential exists. There is little or no effect on the system | **2** |
| No effect | No danger | Failure causes no injury and has no impact and the system | **1** |

**Table 3.1:** FMECA severity table rating scale [36, 37]

| Likelihood of failure | Description | Criteria: Occurrence of Cause (incidents per items/machines) | Rank |
|---|---|---|---|
| Very high | Certain probability of occurrence. Failure is inevitable | ≥ 100 per thousand<br>≥ 1 in 10 | 10 |
| | Failure is almost inevitable | around 50 per thousand<br>1 in 20 | 9 |
| High | High probability of occurrence. Repeated failures | around 20 per thousand<br>1 in 50 | 8 |
| | Moderately high probability of occurrence. Repeated failures | around 10 per thousand<br>1 in 100 | 7 |
| Moderate | More than moderate probability of occurrence. Frequent failures | around 2 per thousand<br>1 in 500 | 6 |
| | Moderate probability of occurrence | around 0.5 per thousand<br>1 in 2000 | 5 |
| | Occasional failure occurrence | around 0.1 per thousand<br>1 in 10000 | 4 |
| Low | Low probability of occurrence. Few failures | around 0,01 per thousand<br>1 in 100000 | 3 |
| | Sparse probability of occurrence. Very few failures | ≤ 0.001 per thousand<br>1 in 1000000 | 2 |
| Very low | Remote probability. Failure is unlikely | Failure is eliminated through preventive control | 1 |

**Table 3.2:** FMECA occurrence table rating scale [36, 37]

| Likelihood of detection | Opportunity of detection | Criteria: Likelihood of Detection by Process Control/In-service detection | Rank |
|---|---|---|---|
| Almost impossible | No detection opportunity | There is no known mechanism for detecting cause mechanism and subsequent failure | 10 |
| Very remote | Not likely to detect at any stage. Remote/unreliable chance of detection | Failure mode/cause are not detectable in-service. The failure can be detected only with a thorough inspection and this is not feasible or cannot be readily performed. Remote chance that process control detect cause mechanism and subsequent failure in offline unplanned monitoring | 9 |
| Remote | | | 8 |
| Very Low | Remote chance of detection | The error can be detected with manual inspection. Failure mode/cause is possibly detected by offline planned periodic testing or monitoring | 7 |
| Low | Moderate chance of detection | Low chance that process control detects cause mechanism and subsequent failure online. Failure mode/cause is most likely detected by offline planned periodic testing or monitoring | 6 |
| Moderate | | | 5 |
| Moderately high | High chance of detection | There is 100% inspection or review of the process. High chance that process control detects cause mechanism and subsequent failure. Failure mode/cause is possibly detected by online automatic continuous testing or monitoring | 4 |
| High | | | 3 |
| Very high | Very high chance of detection | 100% inspection or review of the process and it is automated. Current control almost certain to detect cause mechanism and subsequent failure online | 2 |
| Almost certain | Almost certain chance of detection. Error prevention | There are automatic "shut-offs" or constraints that prevent failures. Failure mode/cause is always detected online by automatic continuous testing | 1 |

**Table 3.3:** FMECA detectability table rating scale [36, 37]

In order to assign a value to the severity (S), occurrence (O) and detectability (D) parameters, the previous tables, taken from [36, 37], Tab. 3.1 for severity, Tab. 3.2 for occurrence and Tab. 3.3 for detectability will be used as models. Then values will be assigned to the parameters relating to each failure mode depending on the specific in-depth analysis performed on the component, data collected through extensive literature research, and personal judgment of the author.

## 3.2 Electric Motors

Electric motors play a very important part in supplying power for all types of industrial applications. The reliability of an electric motor is dependent upon the reliability of its constituent parts, which may include: bearings, electrical windings, rotor, stator, shaft, housing, and brushes. The total motor system failure rate is the sum of the failure rates of each of the parts in the system.
Electrical machines and drive systems are subject to many different types of faults, but it's important to keep in mind that the majority of all motor failures are caused by a combination of various stresses acting upon the winding, stator, rotor, bearings, and shaft.
The main faults of electrical machines can broadly be classified as the following:

1. **stator faults**: defined by stator windings open or short circuited;
2. **rotor electrical faults**: which include rotor winding open or short circuited for wound rotor machines, broken bar(s) or cracked end-ring for squirrel-cage machines and demagnetization for permanent magnet machines;
3. **rotor mechanical faults**: bearing damage, eccentricity, bent shaft, misalignment etc;
4. failure of one or more external power electronic component of the drive system.

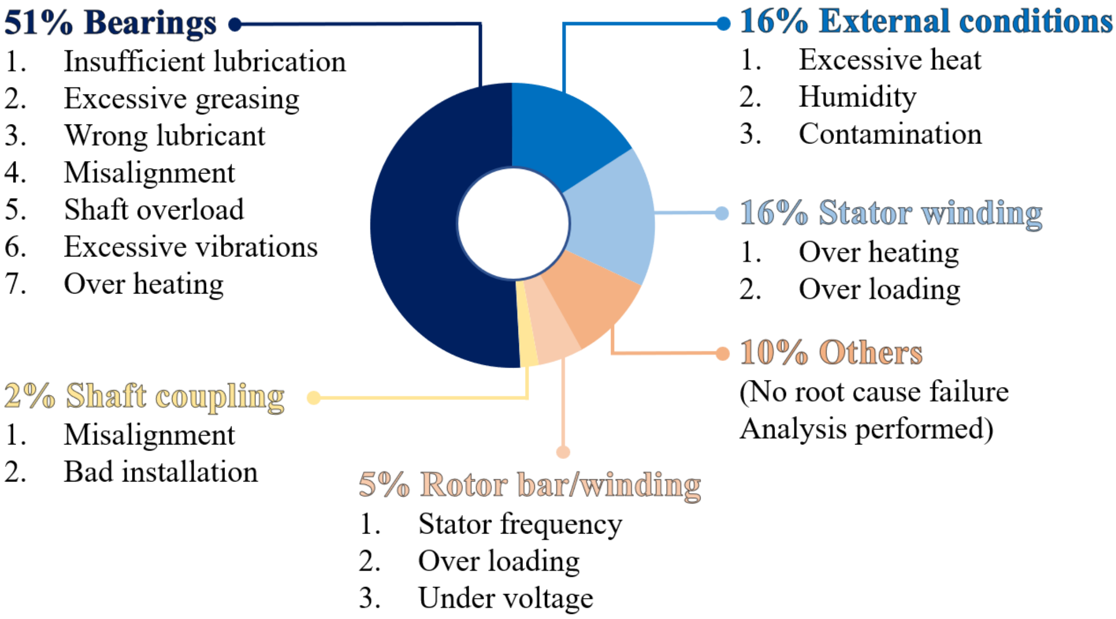


**Figure 3.1:** Overview on motor failure frequency [39]

As shown in figure 3.1, among the above types of faults, bearing, stator or armature faults, broken rotor bar and end ring faults (or rotor winding faults), and the eccentricity-related faults are the most prevalent ones and, thus, demand special attention. These faults, as stated in [40], produce one or more of the following symptoms:

1. unbalanced air-gap voltages and line currents;
2. increased torque pulsations;
3. decreased average torque;
4. increased losses and reduction in efficiency;
5. excessive heating.

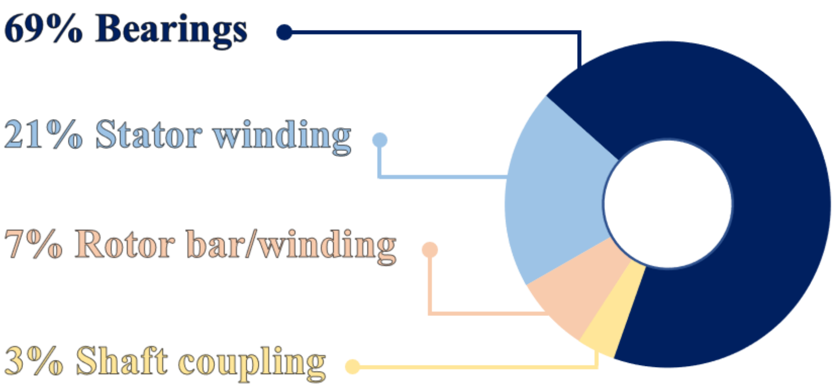


**Figure 3.2:** Focus on motors component failure [41]

Considering just the components of the motor, without accounting for those slices which in Fig. 3.1 are referred to as "external conditions" and "others" (which are failures with no root cause analysis performed), the distribution of induction motor faults, as can be seen in Fig. 3.2, as listed in [41] is:

- bearing (69%);
- stator windings (21%);
- rotor bar or rotor windings (7%);
- shaft coupling (3%).

Considering the case of electric motors, in order to make the analysis more structured, the possible fault root causes can be distinguished into two main category: electrical causes (e.g. currents and voltages asymmetry) and mechanical causes (e.g. vibrations).

### 3.2.1 Electrical faults

In this section the main faults that can be traced back to electrical root causes will be analyzed.

- **Stator or Armature Faults**

  These faults are usually related to insulation failure. They are commonly known as phase-to-ground or phase-to-phase faults. It is believed that these faults start as undetected turn-to-turn faults that finally grow and culminate into major ones.
  It's notable that 16% of motor failures are stator winding related (based on IEA, International Energy Agency data [39]), and raise to 21% of all reported motor failure when considering just the motor component, without accounting for external conditions, according to [41].

  Armature or stator insulation can fail due to several reasons [40]. Primary among these are:

  1. high stator core or winding temperatures (temperature rise occurs in a motor due to copper and iron losses in normal operating conditions);
  2. slack core lamination, slot wedges, and joints;
  3. loose bracing for end winding;
  4. contamination due to oil, moisture, and dirt;
  5. short circuit or starting stresses;
  6. electrical discharges;
  7. leakage in cooling systems (temperature rise inside the motor depends on how effectively this heat can be removed by the cooling system);
  8. over-loading at the motor shaft which causes excessive heat build-up and vibrations.

Therefore it is possible to guess that most of the defects are due to the stator windings issues. The life expectancy of a motor winding is primarily dependant on its operating temperature with respect to the permitted temperature rise of the winding [42]. Excessively high temperature will accelerate the aging process of the insulation materials, until the moment when the materials lose their insulating properties and break down causing short circuits.
Two main classes of stator winding failures can be considered:

1. asymmetry in the stator windings such as an open-phase failure;
2. short-circuit of a few turns in a phase winding.

The former allows the machine to operate with a reduced torque while the latter leads to a catastrophic failure in a short time. It is important to underline that for prognostic purposes, the short circuit will therefore be much more difficult to identify in an incipient state, as the transition from fault to failure occurs quickly.
A short circuit is indeed recognized as one of the most difficult failures to detect. The usual protection might not work or the motor might keep on running while the increased heat in the shorted turns would soon cause critical insulation breakdown. If left undetected, turn faults will propagate, leading to phase-ground or phase-phase faults. Ground current flow results in irreversible damage to the core, and the machine must be removed from service. Incipient detection of turn faults is therefore mandatory.

- **Broken Rotor Bar and End-Ring Faults**
  Rotor failures account for around 5% - 7% of total induction motor failures [40]. The reasons for rotor bar and end-ring breakage are several and according to Nandi et al. can be distinguished in the following:

  1. **thermal stresse**s due to thermal overload and unbalance, hot spots, or

excessive losses, sparking (mainly fabricated rotors);

2. **electromagnetic stresses** caused by electromagnetic forces, unbalanced magnetic pull, electromagnetic noise, and vibration;
3. residual stresses due to **manufacturing problems**;
4. **dynamic stresses** arising from shaft torques, centrifugal forces, and cyclic stresses;
5. **environmental stresses** caused by, for example, contamination and abrasion of rotor material due to chemicals or moisture;
6. **mechanical stresses** due to loose laminations, fatigued parts, bearing failure;
7. **over-heating**: excessively frequent switching on and off are a major cause of over-heating. During start-up a motor typically sees between six to eight times its rated current. This increases the thermal status of the motor, increases thermal stress on the windings and can cause failure.

The broken bar effects on the motor stator current were largely treated in the literature [40, 43, 44]. It was shown that this fault produces a relatively significant localized disturbance of the magnetic flux in the airgap, and gives rise to a periodic variation of the induction motor load torque (oscillations present at particular frequencies, often related to the shaft speed). In the case of stator faults, machine operation after the fault is limited to a few seconds, while in case of rotor faults, the machine operation is not restricted apart from a suitable precautionary measure during maintenance.

On the other hand, the current in the rotor bars adjacent to the faulty one increases up to 50% of the rated current, so Motor Current Signature Analysis (MCSA) has been extensively used to detect broken rotor bar and end-ring faults in induction machines [45, 46].

### 3.2.2 Mechanical faults

Mechanical faults typically account for 53% of induction motor failures (indicated as "bearing" and "shaft coupling" in Fig. 3.1) going up to a major 72% if the focus is only on the components (Fig. 3.2). These faults refer to damage in rolling element bearings, static and dynamic eccentricities.

- **Bearing Faults**

  Bearing is a mechanical component which consists of two rings and a set of balls rolling between them and it has been recorded as one of the dominant causes for electric machine breakdown. Failure could be caused by:

  1. metal fatigue;
  2. unbalanced stress;
  3. improper installation;
  4. corrosion/contamination;
  5. insufficient lubrication/wrong lubricant/excessive greasing;
  6. shaft overload;
  7. vibration;
  8. over-heating.

  More than 51% of motor failures are bearing related (based on IEA data) [39]. Bearing related failures will be developed in the upcoming section 3.5. Since bearing fault manifests itself as a vibration of rotor and unbalance air gap length (rotor asymmetry faults), which are usually covered under the category of eccentricity-related faults, it is sometimes also classified in the eccentricity category.

- **Eccentricity-related Faults**

  Eccentricity in an electric machine is a condition of uneven air-gap that exist between stator and rotor. If this condition becomes severe, the resulting unbalanced radial forces, also known as Unbalanced Magnetic Pull or UMP, can cause rotor-to-stator rub, and this can result in damage to both the stator and rotor. Airgap eccentricity is one of the most common failure conditions in an induction machine since it can occur even before the electric machine installation, like during the manufacturing process or shipping.

  Usually, there are interactions between the faults. An eccentricity may be caused by many problems such as bad bearing positioning during the motor assembly, worn bearings, bent rotor shaft, coupling misalignment or operation under a critical speed creating rotor whirl. Eccentricity generates a force on the rotor that attempts to pull the rotor from the stator bore. It also causes excessive stressing during motor operating cycle and greatly increases the bearing wear and overall motor noise. Furthermore, the radial magnetic force owing to the eccentricity can also act on the stator core and exposes the stator windings to unnecessary and potentially harmful vibration.

  The eccentricity of a cylinder rotating around an airgap can be classified into three types: static, dynamic, or mixed eccentricity.

  1. **Static eccentricity:** this condition is shown in Fig. 3.3.b. The center of rotation is simply displaced from the original center by a certain quantity. The position of the minimal radial air-gap length is fixed in space. Static eccentricity may be caused by the ovality of the stator core or by the incorrect positioning of the rotor or stator at the commissioning stage. If the rotor-shaft assembly is sufficiently stiff, the level of static eccentricity does not change.

  2. **Dynamic eccentricity:** the center of rotation is still at its origin while

the cylinder is displaced, resulting in the center of the rotor not being at the center of the rotation and the position of minimum air-gap rotates with the rotor (Fig. 3.3.c). This misalignment may be caused due to several factors such as a bent rotor shaft, bearing wear, mechanical resonance at critical speed, etc.

3. **Mixed eccentricity:** both the cylinder and the center of rotation are displaced from their respective origin, as can be seen in Fig. 3.3.d.

All types of eccentricity can be related to both torque and speed oscillations. Moreover, dynamic eccentricity produces a mechanical unbalance in the form of a centrifugal force rotating at rotor speed which leads to vibrations at the same frequency.

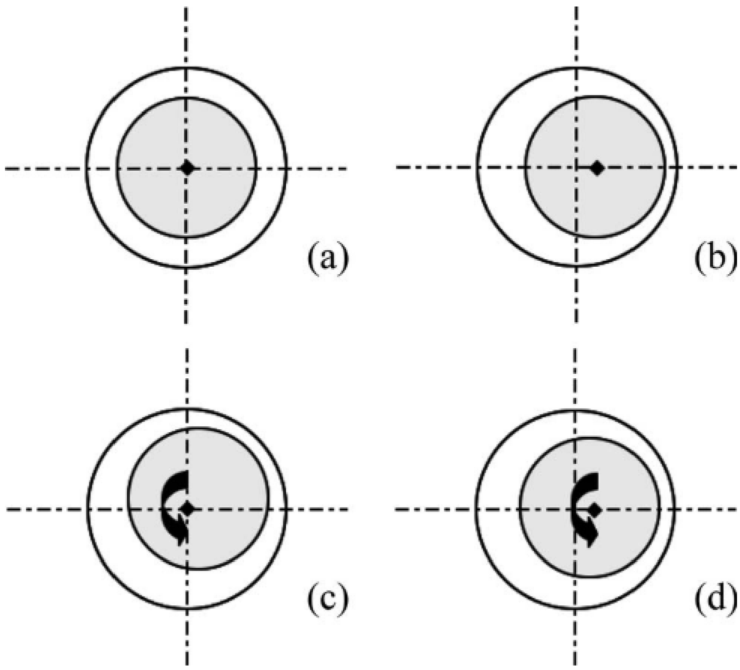


**Figure 3.3:** Different types of eccentricity (border line is the stator inner ring, rotor is in gray, dotted lines are centering the stator frame and center of rotation is the symbol ♦). (a) Without eccentricity. (b) Static eccentricity. (c) Dynamic eccentricity. (d) Mxed eccentricity. [46]

- **Permanent Magnet Faults**

  For permanent magnet machines, an additional failure cause involves the permanent magnets, where demagnetization is the most common issue [47]. The demagnetization could be uniform over all poles or partial over certain region or poles.

  Conditions that could cause permanent magnets in a PMSM (Permanent Magnet Synchronous Machine) to demagnetize include:

  1. high operation temperature/cooling system malfunction;
  2. aging of magnets;
  3. corrosion of magnets;
  4. inappropriate armature current.

### 3.2.3 Electric motors case study

The following data are taken from an investigation conducted in 1995 by O. Thorsen and M. Dalva [48] on 2596 cage motors. The aim of this research was to analyze how the failures are distributed on the failed components. Table 3.4 summarizes this distribution. The result of the survey shows, as expected, that bearing faults count for the majority of the failures, as much as about 51%. Faults on stator windings and on external devices amount to about 16% each. These three add to more than 80% of all faults that have led to a failure.

| **Failed component** | **Number of failures** | **Percent [%]** |
|---|---|---|
| Bearing | 836 | 51.07 |
| Stator windings | 258 | 15.76 |
| Rotor bar/Rotor rings | 77 | 4.70 |
| Shaft or couplings | 40 | 2.44 |
| External device | 255 | 15.58 |
| Not specified | 171 | 10.45 |

**Table 3.4:** EM: failed component distribution

In Table 3.5 the bearing failures are analyzed particularly. However, because of a high rate of “not specified” reasons, an additional column is added to show how the specified reasons are distributed. This table (Table 3.5), reveals that mechanical breakage and overheating are the most frequent failure initiators of bearing failures, whereas high vibration and persistent overloading are the most frequent failure contributors. Improper operation and defective components are the major failure underlying causes. It is possible to find in the Table 3.5, highlighted in yellow, the data relating to the frequency of occurrence of the most common failure initiator, contributor and cause concerning bearing failure in electric motors.

| Bearing Failure and Their Causes | | | |
|---|---|---|---|
| **Bearings - causes of failures** | **Number of failures** | **Percent [%]** | **Percent, excl. "not specified"** |
| **Failure initiator** | | | |
| 1) Transient overvoltages | 0 | 0 | 0 |
| 2) Overheating | 21 | 2.51 | 22.11 |
| 3) Other insulation breakdown | 2 | 0.24 | 2.11 |
| 4) Mechanical breakage | 67 | 8.01 | 70.53 |
| 5) Electrical fault or malfunction | 4 | 0.48 | 4.21 |
| 6) Stalled motor | 1 | 0.12 | 1.05 |
| 7) Not specified | 741 | 88.64 | / |
| **Failure contributor** | | | |
| 1) Persistent overloading | 23 | 2.75 | 22.77 |
| 2) High ambient temperature | 1 | 0.12 | 0.99 |
| 3) Abnormal moisture | 9 | 1.08 | 8.91 |
| 4) Abnormal voltage | 1 | 0.12 | 0.99 |
| 5) Abnormal frequency | 1 | 0.12 | 0.99 |
| 6) High vibration | 51 | 6.10 | 50.50 |
| 7) Aggressive chemicals | 1 | 0.12 | 0.99 |
| 8) Poor lubrication | 13 | 1.56 | 12.87 |
| 9) Poor ventilation or cooling | 1 | 0.12 | 0.99 |
| 10) Normal deterioration from age | 0 | 0.00 | 0.00 |
| 11) Not specified | 735 | 87.92 | \ |
| **Failure underlying cause** | | | |
| 1) Defective component | 22 | 2.63 | 27.50 |
| 2) Poor installation/testing | 3 | 0.36 | 3.75 |
| 3) Inadequate maintenance | 9 | 1.08 | 11.25 |
| 4) Improper operation | 30 | 3.59 | 37.50 |
| 5) Improper handling/shipping | 4 | 0.48 | 5.00 |
| 6) Inadequate physical protection | 5 | 0.60 | 6.25 |
| 7) Inadequate electrical protection | 2 | 0.24 | 2.50 |
| 8) Personnel error | 0 | 0.00 | 0.00 |
| 9) Outside agency - not personnel | 3 | 0.36 | 3.75 |
| 10) Motor-driven equipment mismatch | 2 | 0.24 | 2.50 |
| 11) Not specified | 756 | 90.34 | \ |

**Table 3.5:** Bearing failure and their causes [48]

In Table 3.6, the stator winding failures are analyzed particularly. And as for the bearings, the “not specified” percentage is high, so that an additional column is added to show how the specified reasons are distributed. In Tab. 3.6 the lines referring to the most common failure initiator, contributor and cause have been highlighted in yellow. Table 3.6 shows that overheating and other insulation breakdowns are the major failure initiators. The major failure contributor is persistent overloading, and the most frequent underlying causes are improper operation, defective component and inadequate electrical protection.

From this survey, a somewhat unexpected result was that the failure rate was considerably higher with one start per day than with more starts. The starting procedure, especially direct on line start, causes extra stress on rotors, bearings, and coil ends, so one would have expected another result. The explanation must be that fewer starts per day means longer duty time per day.

| Stator Windings Failure and Their Causes | | | |
|---|---|---|---|
| **Stator Windings - causes of failures** | **Number of failures** | **Percent [%]** | **Percent, excl. "not specified"** |
| **Failure initiator** | | | |
| 1) Transient overvoltages | 9 | 3.49 | 7.03 |
| 2) Overheating | 25 | 9.69 | 19.53 |
| 3) Other insulation breakdown | 58 | 22.48 | 45.31 |
| 4) Mechanical breakage | 19 | 7.36 | 14.84 |
| 5) Electrical fault or malfunction | 14 | 5.43 | 10.94 |
| 6) Stalled motor | 3 | 1.16 | 2.34 |
| 7) Not specified | 130 | 50.39 | / |
| **Failure contributor** | | | |
| 1) Persistent overloading | 26 | 10.08 | 52.00 |
| 2) High ambient temperature | 4 | 1.55 | 8.00 |
| 3) Abnormal moisture | 8 | 3.10 | 16.00 |
| 4) Abnormal voltage | 2 | 0.78 | 4.00 |
| 5) Abnormal frequency | 0 | 0.00 | 0.00 |
| 6) High vibration | 3 | 1.16 | 6.00 |
| 7) Aggressive chemicals | 1 | 0.39 | 2.00 |
| 8) Poor lubrication | 0 | 0.00 | 0.00 |
| 9) Poor ventilation or cooling | 2 | 0.78 | 4.00 |
| 10) Normal deterioration from age | 4 | 1.55 | 8.00 |
| 11) Not specified | 208 | 80.62 | \ |
| **Failure underlying cause** | | | |
| 1) Defective component | 12 | 4.65 | 22.64 |
| 2) Poor installation/testing | 3 | 1.16 | 5.66 |
| 3) Inadequate maintenance | 1 | 0.39 | 1.89 |
| 4) Improper operation | 18 | 6.98 | 33.96 |
| 5) Improper handling/shipping | 0 | 0.00 | 0.00 |
| 6) Inadequate physical protection | 5 | 1.94 | 9.43 |
| 7) Inadequate electrical protection | 12 | 4.65 | 22.64 |
| 8) Personnel error | 0 | 0.00 | 0.00 |
| 9) Outside agency - not personnel | 2 | 0.78 | 3.77 |
| 10) Motor-driven equipment mismatch | 0 | 0.00 | 0.00 |
| 11) Not specified | 205 | 79.46 | \ |

**Table 3.6:** Stator windings failure and their causes [48]

### 3.2.4 Stresses classification

In paper [49] it is possible to find a summary of motor stresses which can be classified according to the following tables in:

- rotor stresses;
- stator stresses;
- bearing stresses;
- shaft stresses.

| **Rotor stresses** | |
|---|---|
| **Thermal stresses** | **Mechanical stresses** |
| - Thermal overload | - Casting variations |
| - Thermal unbalance | - Loose laminations |
| - Excessive rotor losses | - Incorrect shaft/core fit |
| - Hot spots | - Fatigue or part breakage |
| - Sparking | - Poor rotor or stator geometry |
| **Magnetic stresses** | - Material deviations |
| - Rotor pullover | - Centrifugal force |
| - Noise | **Environmental stresses** |
| - Vibration | - Contamination |
| - Off magnetic center | - Abrasion |
| - Saturation of lamination | - Foreign particles |
| - Circulating currents | - Restricted ventilation |
| **Residual** | - Excessive ambient temperature |
| - Stress concentrations | **Other** |
| - Uneven bar stress | - Misapplications |
| **Dynamic** | - Poor design |
| - Vibration | - Manufacturing variation |
| - Rotor rub | - Loose bars/core |
| - Overspeeding | - Transient torques |
| - Cyclic stresses | - Wrong direction of rotation |

**Table 3.7:** Rotor assembly stresses [49]

**Stator stresses**

| | |
|---|---|
| **Thermal stresses** | **Mechanical stresses** |
| - Thermal aging | - Coil movement |
| - Voltage variation | - Rotor strikes |
| - Cycling | - Defective rotor |
| - Loading | - Flying objects |
| - Ventilation | - Lugging of leads |
| - Ambient | |
| **Electrical stresses** | **Environmental stresses** |
| - Dielectric aging | - Moisture |
| - Tracking | - Chemical |
| - Corona | - Abrasion |
| - Transients | - Damaged parts |
| | - Restricted ventilation |

**Table 3.8:** Stator stresses [49]

**Bearing stresses**

| | |
|---|---|
| **Dynamic and static loading** | **Electrical stresses** |
| - Radial | - Rotor dissymmetry |
| - Axial | - Electrostatic coupling |
| - Preload | - Static charges |
| **Thermal stresses** | **Environmental stresses** |
| - Friction | - Condensation |
| - Lubricant | - Foreign material |
| - Ambient | - Restricated ventilation |
| **Vibration and shock** | - Excessive ambient temperature |
| - Rotor | **Mechanical** |
| - Driven equipment | - Loss of clearances |
| - System | - Misalignments |
| | - Shaft/Housing fits |

**Table 3.9:** Bearing stresses [49]

| **Shaft stresses** | |
|---|---|
| **Mechanical stresses** | **Thermal stresses** |
| - Overhung load and bending | - Temperature gradient |
| - Torsional load | - Rotor bowing |
| - Axial load | **Environmental stresses** |
| **Dynamic stresses** | - Corrosion |
| - Cyclic | - Moisture |
| - Shock | - Erosion |
| **Residual** | - Wear |
| - Manufacturing process | **- Electromagnetic stresses** |
| - Repair process | - Side loading |
| | - Out of phase reclosing |

**Table 3.10:** Shaft stresses [49]

| **Cause of shaft failures** | **Percent** |
|---|---|
| Corrosion | 29 % |
| Fatigue | 25 % |
| Brittle fracture | 16 % |
| Overload | 11 % |
| High-temperature corrosion | 7 % |
| Stress corrosion fatigue | 6 % |
| Creep | 3 % |
| Wear, abrasion, erosion | 3 % |

**Table 3.11:** Cause of shaft failure [49]

The last table, Tab. 3.11, takes shaft failures into consideration, and shows that corrosion and fatigue account for more than half of shaft failure causes.

All these data will be useful in the construction of the FMECA table, Tab. 3.12, available in Sec. 3.6, as they provide a great contribution being data collected in the operational field. Especially, data coming from the survey [48], will be taken into consideration when computing the RPN, while the stresses classification is of major importance for identifying all possible failure modes.

## 3.3 Harmonic drive

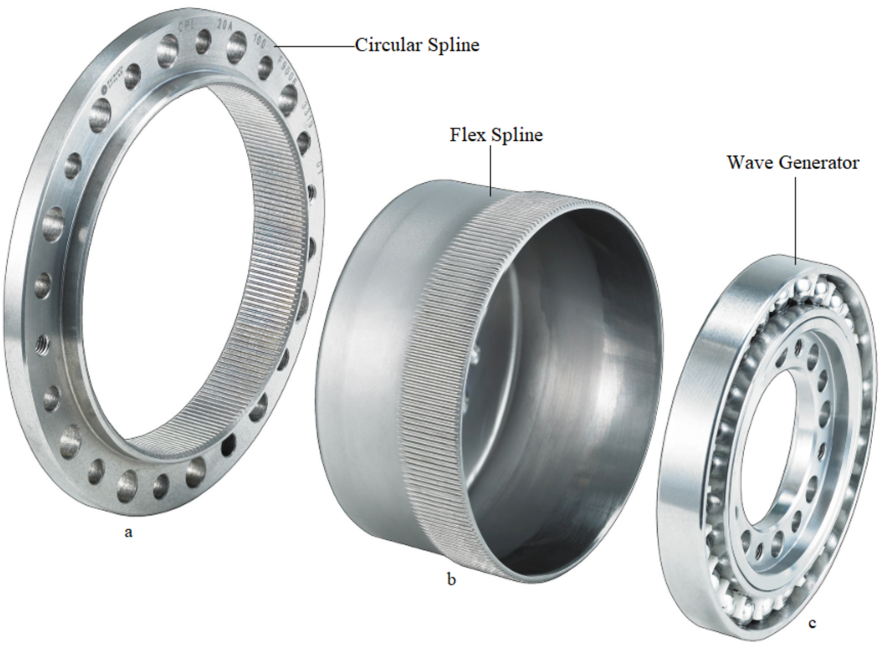


**Figure 3.4:** Harmonic drive components [34]

The focus of this analysis for what concerns the gearbox component of the robotic joint will be on Harmonic Drive ® gearing, since it is the transmission component mounted on the UR5 (Sec. 2.6).
Strain Wave Gearing (SWG), also known as harmonic drive (HD) gear, has been used in many applications that require lightweight and compact mechanical components [50]. Like conventional gears, harmonic gear is used because of its high load carrying capacity, speed reduction, torque amplification, torsional stiffness and power transmission, but unlike conventional gears it is possible to get all of these in a single stage with co-axial shafts in a more precise, compact and lightweight manner, being weight a key aspect when robotic joints are considered. Harmonic gears possess several other characteristics, for instances: lower hysteresis losses (loss of power due to internal friction), zero backlash, small size, high smoothness, minimal

wear, long life, high positioning accuracy, high repeatability and competitive price, without compromising efficiency [20], that is why they are widely used in industrial and collaborative robots as joints drive component.

### 3.3.1 Components and Working Principle

In the following section the Harmonic Drive component set will be described. It consists in three precision components: Circular Spline, Flexspline, which is the component that transmits load to the output, and Wave Generator, which is the driven element of the transmission. A deeper description of these comoponents is needed in order to investigate their possible failure causes.

**SWG components**

Strain wave gearing utilizes a unique operating principle which is based upon the elastic mechanics of metals. The gear mechanism consists of only three major concentric components: Circular Spline, Flexspline and Wave Generator.

- **Circular spline (CS)**

  It is a rigid ring with internal teeth (Figure 3.4.a). It is usually held immobile and it does not carry any motion. When the gear is assembled, it engages the teeth of the Flexspline across the major axis of the Wave Generator ellipse. The Circular Spline has two more teeth than the Flexspline and is fixed to the gear housing [34].

- **Flexspline (FS)**

  It is a non-rigid, thin cylindrical cup made from alloy steel with external teeth on the open end of the cup (Figure 3.4.b). The closed end of the cup is provided with a flange, called boss, and it is used as output port. The Flexspline is radially compliant, but torsionally very stiff. When the Wave Generator is inserted into the Flexspline, the open end of the cup takes on its elliptical shape.

The Flexspline may be subject to repeated vibrations produced by the Wave Generator, therefore it should have good vibration-resistant characteristics [34].

- **Wave Generator (WG)**

  It is composed of a specially designed thin raced ball bearing that is fitted onto an elliptical hub (Figure 3.4.c). This serves as a high efficiency torque converter and is used as the input of the gear connected to the motor shaft [34].

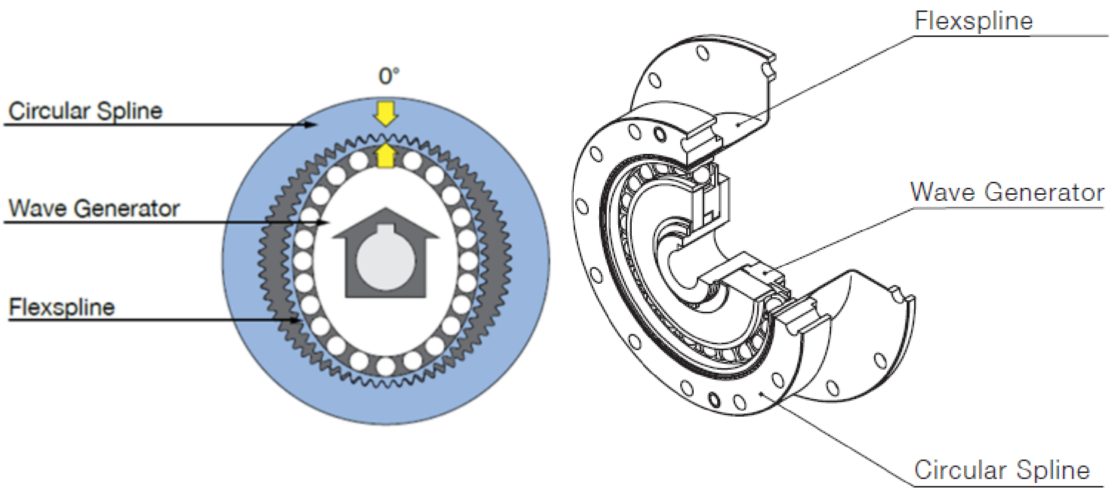


**Figure 3.5:** Assembled Harmonic Drive [34]

This simple three element construction assembled together (Fig. 3.5), combined with the unique operating principle, allows extremely high reduction ratio (from 30:1 to 320:1) in a very compact and lightweight package [34].
The reduction ratio ($\tau$) is not a function of the relative sizes of the toothed components, as is the case for spur gears or planetary gears, but simply of the number of teeth:

$$\tau = \frac{\text{Flex Spline teeth} - \text{Circular Spline teeth}}{\text{Flex Spline teeth}} \tag{3.1}$$

### Working principle

The three basic components function in the following manner: the Flexspline is slightly smaller in diameter and has two fewer teeth than the Circular Spline. The Flexspline is elliptically shaped by the Wave Generator when the latter is inserted in the open end of the cup. The elliptical shape of the Wave Generator causes the teeth of the Flexspline to engage the Circular Spline at two opposite regions across the major axis of the ellipse (20-30% of teeth comes continuously in contact [51]). The teeth completely disengage on the minor axis. As the wave generator (input) rotates, the zone of tooth engagement travels with the major axis of the ellipse. For every 180° clockwise rotation of the Wave Generator, the Flexspline (output) teeth are advanced counter-clockwise by one tooth in relation to the Circular Spline (fixed). Each complete clockwise rotation of the Wave Generator results in the Flexspline moving counter-clockwise by two teeth from its original position relative to the Circular Spline. Because the gear teeth are always fully engaged in a region along the major axis, Harmonic Drive strain wave gearheads have ideally zero backlash [34, 50]. The zero backlash characteristic obviously deteriorates when teeth wear occurs which affects the performance of the component

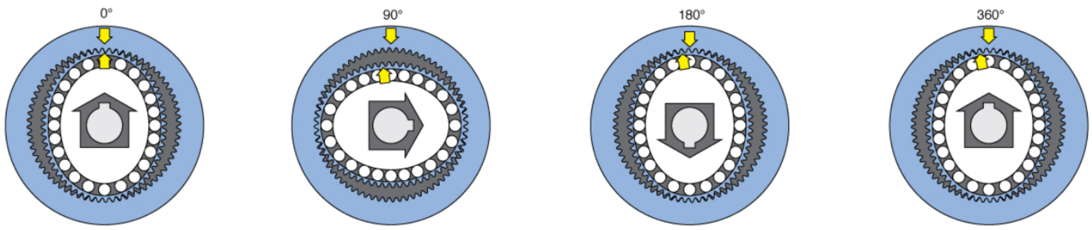


**Figure 3.6:** Harmonic Drive working principle [34]

### 3.3.2 Possible causes of non-nominal behaviour

The reliability of a gear and other gearbox components is an extremely important consideration in the design of a power transmission system, ensuring that the required loads can be handled for the expected life of the system, providing in the meantime accurate and repeatable motion especially for robotic applications that need high accuracy and reliability.
The more common modes of gear failure, according to [42], are wear, surface fatigue, plastic flow (which refers to when high contact stresses cause the gear tooth surface to become deformed) and breakage. In the shear mode, the gear immediately ceases to transmit power while in the wear mode it degrades gradually before complete failure. For this reason wear is more likely to be identified through a prognostic approach.

#### Wear

Wear is the removal of metal, worn away normally in a uniform way from the contacting surface of the gear teeth. The first stage of wear, indicated as normal wear, is the polishing phase during which gear asperities of the contacting surfaces are gradually worn off until very fine, smooth surfaces develop. At this stage, wear is not identified as a damage. Moderate wear occurs most commonly when the gear is operating in or near the boundary lubrication regime. Many gears, because of practical limits on lubrication viscosity, speed and temperature, must of necessity operate under such conditions. Moderate wear consists in small quantity of material scraped away from the tooth surface. Critical or excessive wear is similar to moderate wear but the gear teeth are experiencing a considerable amount of material being removed from the surfaces. During this phase the wear expands until the tooth profile gets out of the shape, the gear can not be properly meshed anymore so high dynamic loads are encountered which in turn accelerates the

wear rate until the gear is no longer usable. In general, contamination of the lubricant with these detached particles can accelerate wear, that can thus be seen as a self-feeding damaging process.
Indeed, as stated in [34, 50, 52], most SWG reaches its normal rated lifetime because of a rolling fatigue of wave generator bearing or a worn-out of flexspline tooth.

A life-test experiment was conducted by K. Ueura et al. in [50] where, in order to keep track of wear, contact electric resistances were measured at three moving combinations, identifying three regimes from the voltage–resistance relationship: (a) 0 mV, continues metallic contact (boundary lubrication); (b) 0–49.5 mV, partial metallic contact (mixed lubrication); and (c) 49.5 mV, complete separation (hydrodynamic lubrication).
The analyzed interfaces were:

1. inner/outer races of wave generator bearing:
   the wave generator bearing operates in an almost mixed lubrication regime. The fraction of metal-to-metal contact decreases as the input rotational speed and the environmental pressure increase;

2. wave Generator/Flexspline interface:
   It is the more sensitive to environmental pressure. At atmospheric pressure the wave generator–flexspline interface works under mixed lubrication regime when increasing the input rotational speed. Whereas the lubricating condition in this interface become severe in vacuum operations leading towards critical wear condition due to lubricant starvation in vacuum.

3. flexspline/Circular Spline interface;
   The contact teeth between Flexspline/Circular Spline is under mixed lubrication regime. The fraction of metal-to-metal contact decreases slightly as the input rotational speed and the environmental pressure increase.

It should be noted that vacuum behavior has been tested because this component is often used in space applications. The tests indicate that the lubrication at the wave generator–flexspline interface is crucial for the long operational life of SWG and therefore it may be necessary to monitor more accurately this interface.

Another distinction can be carried out between different type of wear:

- **abrasive wear** caused by an accumulation of abrasive particles in the lubrication;
- **corrosive wear** caused by water or additives in the lubricating oil resulting in a deterioration of the gear surface from chemical action;
- **scuffing/scoring** caused by failure of the lubricant film due to overheating resulting in metal-to-metal contact and alternate welding and tearing of the surface metal.

Other experiments were conducted by Smith et al. [53] in order to monitor the wear of the teeth. It was showed that a sign that the gear set is beginning to wear is obtained when the temperature increases and efficiency decreases. The test ran at the 100 rpm input speed with the load of 33 Nm applied. Signs of wear start at around 100,000 revolutions as shown in the graph reported in Fig. 3.7.

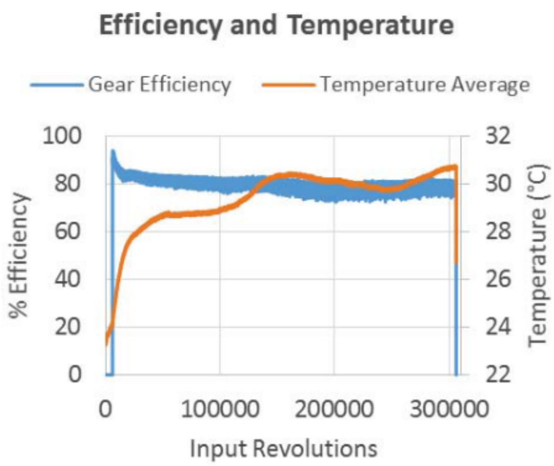


**Figure 3.7:** Temperature rise with respect to efficiency [53]

### Manufacturing defects

Manufacturing defects are one of the main causes of kinematic errors (difference in expected output position to the actual output position), which can occur due to assembly and physical imperfections on the three principal elements of drive, tolerances, or due to the deformation of the flexspline when it takes on the shape of the wave generator. Vibrations can also affect precision, leading to kinematic errors. WG and FS are the two components that produce vibrations being the Wave Generator ball bearing the main cause [51].

### Peak Torque

During acceleration and deceleration, the harmonic drive gear experiences a peak torque as a result of the moment of inertia of the output load. Harmonic drive gearing may be subjected to momentary peak torques in the event of a collision or emergency stop. The magnitude and frequency of occurrence of such peak torques must be kept to a minimum and they should, under no circumstance, occur during normal operating cycle. The allowable number of occurrences of the momentary peak torque may be calculated using the fatigue life for the Flexspline:

$$N = \frac{1 \times 10^4}{2 \times \frac{n}{60} \times t} \tag{3.2}$$

where:

$N$ = maximum number of occurrences;

$n$ = input speed before collision;

$t$ = time interval during collision.

Note that if this number is exceeded, the Flexspline may experience a fatigue failure [34].

### Ratcheting phenomenon

When excessive torque is applied while the harmonic drive gear is in motion, the teeth between the Circular Spline and Flexspline may not engage properly. This phenomenon is called "ratcheting" and the torque at which this occurs is called "ratcheting torque". Ratcheting may cause the Flexspline to become non-concentric with the Circular Spline. Operating in this condition may result in shortened life and a Flexspline fatigue failure. Vibration and Flexspline damage may occur. Once ratcheting occurs, the teeth wear excessively and the ratcheting torque may be lowered [34].

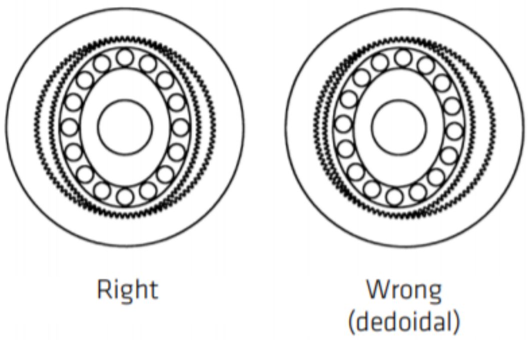


**Figure 3.8:** Lack of coaxiality between flexspline and circular spline due to the ratcheting phenomenon [34]

### Grease Condition

The wear characteristics of harmonic drive gearing are strongly influenced by the condition of the grease lubrication. The condition of the grease is affected by the ambient temperature, environmental pressure and operational speed. The graph in Figure 3.9 shows the maximum number of input rotations for various temperatures. This graph applies to applications where the average load torque does not exceed the rated torque [34].

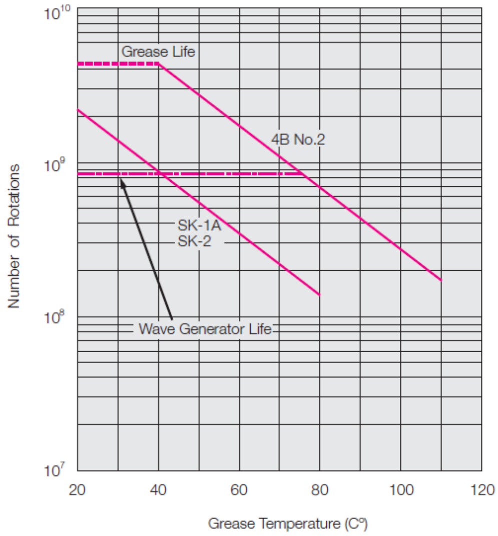


**Figure 3.9:** Grease condition as a function of number of rotations versus temperature [34]

### Axial force of wave generator

When a harmonic drive gear is used to accelerate a load, the deflection of the Flexspline leads to an axial force acting on the Wave Generator. This axial force, which acts in the direction of the closed end of the Flexspline, must be supported by the bearings of the input shaft (motor shaft). When a harmonic drive gear is used to decelerate a load, an axial force acts to push the Wave Generator out of the Flexspline cup, as shown in Fig. 3.10 [34, 54].

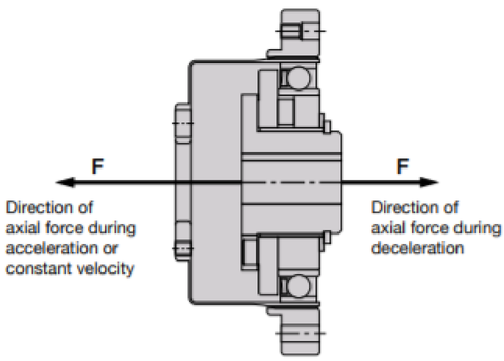


**Figure 3.10:** Axial force direction of the wave generator [34]

The axial force may vary depending on its operating condition. The value of axial force tends to be a greater number when using high torque, extreme low speed and constant operation. The maximum axial force of the Wave Generator is calculated (approximately) by the equation below [34, 54].

| Gear ratio: | Equation: |
|---|---|
| i = 80:1 and above | $F_{ax} = 2 \times \frac{T}{D} \times \mu \times \tan(20°)$ |

Where:

$F_{ax}$ = axial force [N];

$D$ = gearbox size factor (given by manufacturer);

$T$ = output torque [Nm];

$\mu$ = coefficient of friction at the FS/WG interface.

Evaluation of the gradient of a plot of axial load versus output load allows a calculation of the friction coefficient at the WG/FS interface and thus the detection of tribological changes at that interface [54].

### Crack on the rear cross section of the Flexspline

When there are some manufacturing defects in the Flexspline (Fig. 3.11), like in the following example taken from [53], a crack can propagate around the outside circumference of the flexspline giving the result showed in Figure 3.12, because the torsional stiffness is compromised. Those results come from a test conducted at around 100 K, but the crack propagation would have been the same at room temperature, just slower.

For the structure of Flexspline reference is made to Figure 3.17. A defect/crack in the rear cross section of the Flexspline is likely to propagate fast because this area connects two different movements: wave of the gear cross section elliptically deformed by the Wave Geneator and rotation of the boss, closed end part of the

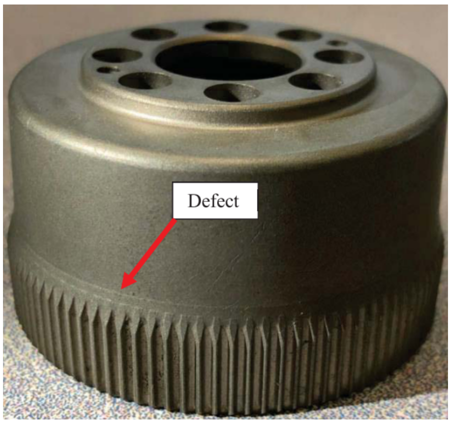


**Figure 3.11:** Manufacturing defect on a Flexspline [53]

**Figure 3.12:** Broken Flexspline after test [53]

flexspline, where the load is attached, thus the rear cross section is subjected to major stress.

Since the teeth portion of the FS is expanded outwardly as shown in Fig. 3.13 by means of the wave generator, the tooth trace of the FS, having been deformed, does not become in parallel to the tooth trace of the circular spline, so that a coning angle $\alpha$ is formed at the teeth portion. Due to the coning angle (Fig. 3.13) the Wave Generator touches the inner part of the Flexspline along an arc, as shown in Figure 3.14, and not along all the thickness of the elliptical hub. This leads to higher stresses on the rear cross section of the Flexspline.

As reported in [56], coning angle $\alpha$ can lead to tooth and bearing wear. Coning

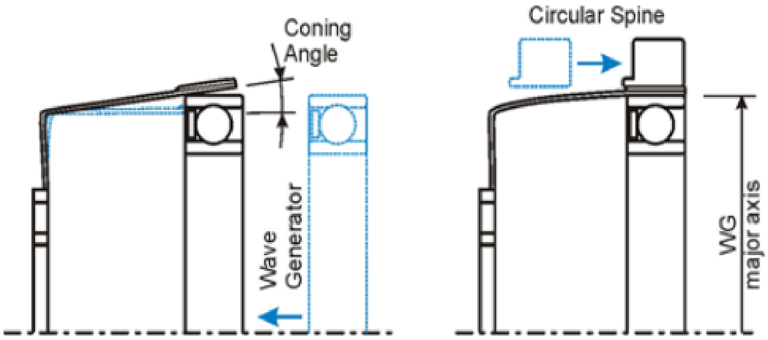


**Figure 3.13:** Coning of the Flexspline [52]

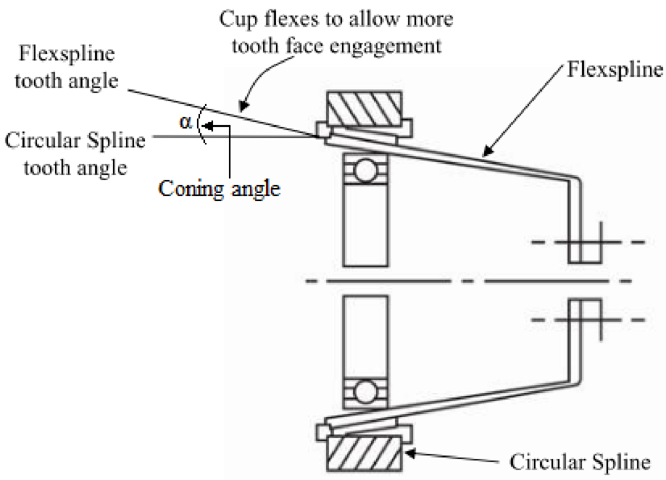


**Figure 3.14:** HD cross section - tooth angle [55]

angle causes the meshing depth between the external teeth of the flexspline and the inner teeth of the circular spline to differ in the tooth-width direction (that is, the shaft line direction of the flexspline). Since the meshing depth differs in the tooth-width direction, the load is not applied uniformly over the entire width of the tooth but it is applied mainly to the front portion of the tooth, concentrically. This can increase the likelihood of having **plastic flow** failure phenomenon. Thus usually, being each of the external teeth of the flex spline and the inner teeth of the circular spline a spur tooth, a normal meshing state can not be obtained between these spur external teeth. Further, due to the influence of the aforesaid coning angle $\alpha$, the wave generator is made in contact only on its one end side with the inner diameter portion of the flexspline (viewed along the shaft line direction of the flexspline). Thus, the life time of the bearing attached between the wave generator and the flexspline is reduced and the meshing rigidity between the wave generator and the flexspline is also degraded.

A research conducted by Roberts et al. [54] claimed that a possible way to figure out the presence of a crack is to study the variation of the stiffness $K_t$ [Nm/rad] compared to the nominal case. When the load of torque increases, the cup flexes to allow more width of flexspline to engage with the circular spline, and the stiffness increases as a consequence. Measurement of stiffness is achieved by locking the input shaft, applying torque to the output shaft (using the motor gear-head) and measuring angular displacement with the output-shaft encoder [54]. The Flexspline deformation is not constant along its surface since there exists a coning angle $\alpha$ between flexspline and circular spline along rotation axis, as shown in Fig. 3.14, so the front cross section has a bigger displacement with respect to the rear cross section. This means that there is an higher probability for a crack generated on the gear cross section to propagate towards the Flexspline mounth, which is the open end of the cup where the WG is inserted, leading to a catastrophic failure of the component [55] as can be seen in Fig. 3.15.

**Figure 3.15:** Catastrophic failure of the Flexspline [55]

### Flexspline failure

The flexspline is one of the most critical components in the whole transmission system [57]. In practical application, it is subjected to transformation stress and cyclic loading, and is prone to fatigue failure. After use for a period of time, the flexspline can be damaged or even broken due to the oxidation and adhesion of the surface of the gear teeth. These phenomena are not only detrimental to the smooth transmission of the system, but also cause production accidents. Gear teeth profile of failed flexspline is shown in Fig. 3.16. Obvious cracks were observed at the tooth root of the failed flexspline (Fig. 3.16.a); local spalling and wear were found near the top of the tooth surface, being more serious in the vicinity of the fracture area. Wave Generator and Flexspline of harmonic gear drive were apt to vibrate under the condition of heavy load and high speed, thus the meshing between flexspline and circular spline was interfered, and the tooth top part of the failed flexspline had strict abrasion, even appears flange and burr (as clearly visible from Fig. 3.16.b) [57].

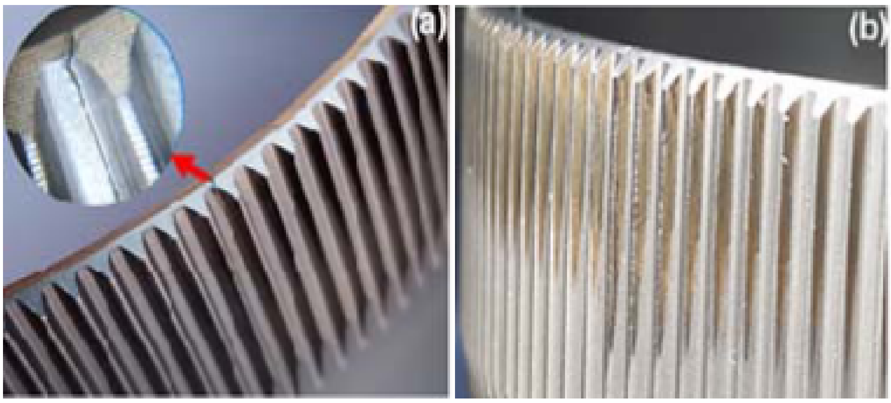


**Figure 3.16:** Gear teeth profile of a failed Flexspline [57]

From the study conducted by J. Zheng and W.Yang in [57], it was found that the weakest region, where there is the highest stress concentration and alternating stress, is the tooth root. Here it is more likely for a crack to form and develop.

The main reason for the failure of the flexspline was that the working surface of the gear has local micro cracks, which results in abnormal contact and local rupture during the working process, thus the dimensional accuracy becomes worse and the service life is reduced.

In harmonic reducer, flexspline is the weakest link because its deformation and stress were caused by both the stretching effect of wave generator and the meshing force between flexspline and circular spline [58]. The harmonic reducer main failure forms are fatigue fracture of roots and wear of tooth surface. However, the complex load conditions of robots, which is not a simple shaft that rotates, but there are continuous changes in speed, acceleration and payload due to different configurations, may have a tremendous impact on the reducer and even increase the possibility of its failures. So the deformation and stress calculation and analysis of flexspline with different loads are of great significance.

In Fig. 3.17 it is possible to check to what reference is made when talking about different cross sections.

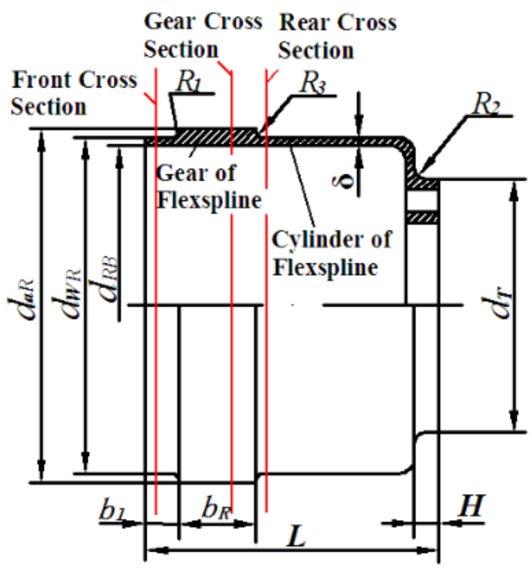


**Figure 3.17:** Flexspline structure [58]

In [58], Zou et all. developed two kind of analysis.

1. **Deformation Analysis**: deformation of flexspline both with load and without load. The maximum deflection point is at the major axis of wave generator and the minimum deflection point is at the point 45° away from minor axis of wave generator. With load, the deflection distribution of flexspline at gear cross section rotates clockwise about 45°.

2. **Flexspline Stress Analysis**: From stress analysis conducted in [58] both with load and without load, it was found that the highest value of stress is at the gear cross section, where the CS and the FS engage, so in this region is more likely for a crack to initiate and propagate. The critical direction for crack propagation is from the gear cross section to the front cross section (the open end of the Flexspline), since it would "open" the Flexspline causing an important damage to the torsional stiffness and to the meshing. If the crack propagates from the gear cross section to the rear cross section, the fracture should be less critical having a weaker influence on the torsional stiffness and on the meshing with the Circular Spline.

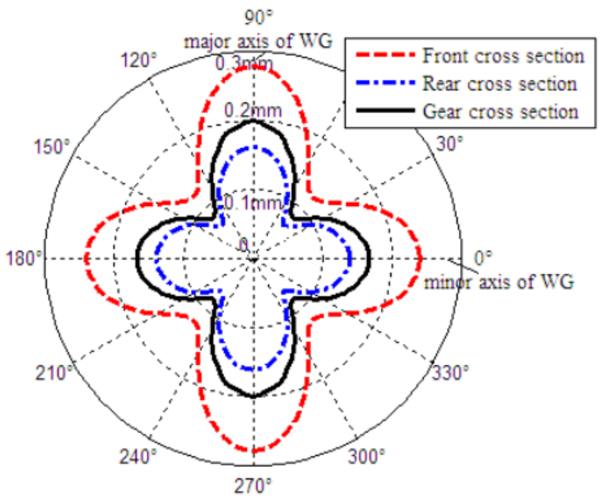


**Figure 3.18:** Radial distribution of Flexspline cylinder deflection without load [58]

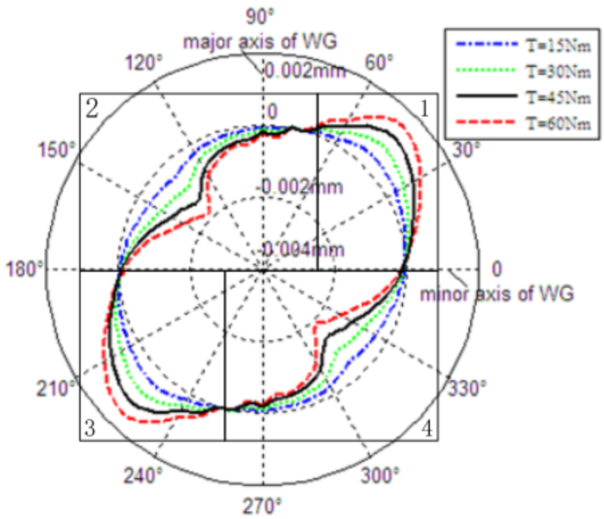


**Figure 3.19:** Flexspline cylinder deflection increment at gear cross section with load [58]

If there is a resistant torque at the output of the hamonic drive, there is an additional displacement of the FS due to a torsion of it and the maximum displacement is reached at about 45° from the major axis of WG in the direction of the load, as it can be seen in Fig. 3.19.

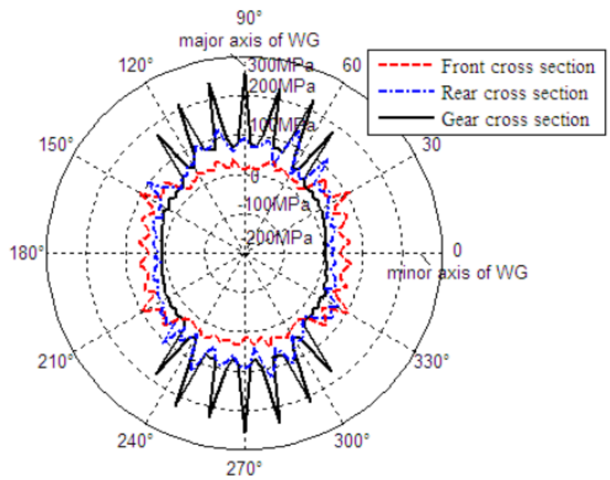


**Figure 3.20:** Radial distribution of Flexspline cylinder stress without load [58]

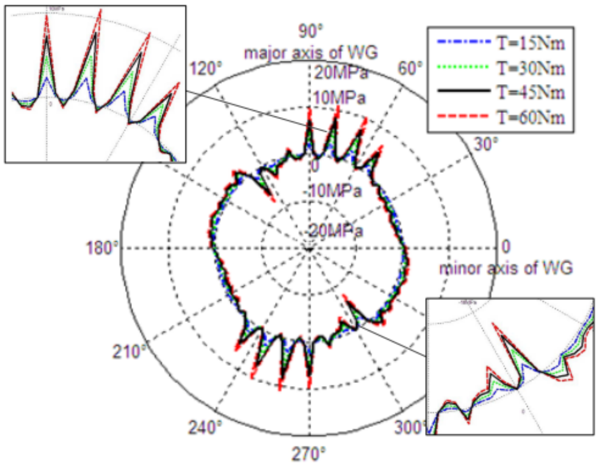


**Figure 3.21:** Flexspline cylinder stress increment at gear cross section with load [58]

In Fig. 3.20 and Fig. 3.21 it is possible to see the FS stress without and with load. It is important to notice that the loaded section of the FS is not just the one corresponding to the major axis, but it comprises all the meshing zone around it (±30° from the major axis).

### Tooth and rim crack/fracture

Before proceeding with the analysis of the crack that follows in this section, it is important to make an aside: for this study in particular, spur gears were considered as a first approximation since in literature very little research has been done regarding the crack in the FS/CS teeth and rim.

In [59] studies were performed to investigate the effect of rim thickness on gear tooth crack propagation. Two possible cracks can occur: through gear teeth (non-catastrophic) or through gear rims (catastrophic). Gear tooth or rim fatigue failures may occur due to several causes: insufficient rim thickness, severe operating conditions such as overload or misalignment, operation near the resonance frequency of the gear structure, or localized wear such as fretting at a gear-shaft connecting joint.

**Fracture modes on the Flexspline:**

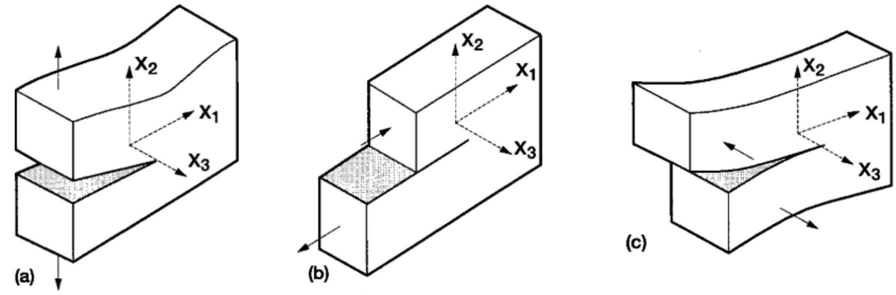


**Figure 3.22:** Fracture modes. (a) Mode I. (b) Mode II. (c) Mode III. [59]

For Mode I (Fig. 3.22.a), the load is applied normally to the crack plane and tends to open the crack, whereas Mode II (Fig. 3.22.b) refers to in-plane shear loading or sliding, finally Mode III corresponds to out-of-plane loading or tearing. Mode I is the most dangerous one since it leads to a faster crack propagation.
In order to figure out where the crack propagation is more likely to happen, it was used a parameter describing the ratio between the rim thickness and the tooth height, the **backup ratio**, indicated with b, and graphically shown in Fig. 3.23:

$$b = \frac{\delta}{h} \tag{3.3}$$

where $\delta$ is the rim thickness and $h$ is the tooth height.
In [59] it was found that if:

- $b \geq 1$ : tooth fracture occurs, regardless of the orientation of the initial crack, as can be seen in Fig. 3.24.a;
- $b \leq 0.5$ : rim fracture occurs, regardless of the orientation of the initial crack, as shown in Fig. 3.24.c;
- $0.5 < b < 1$ : depending on the orientation angle of the initial crack, tooth fracture or rim fracture can happen (Fig. 3.24.b).

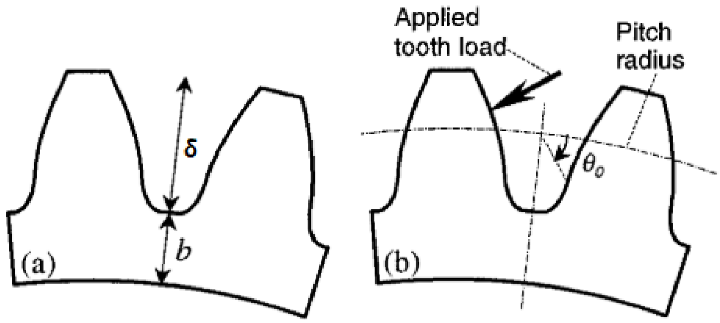


**Figure 3.23:** Definition of terms. (a) Backup ratio, $b = \frac{\delta}{h}$; (b) Initial crack location angle, $\theta_0$. [60]

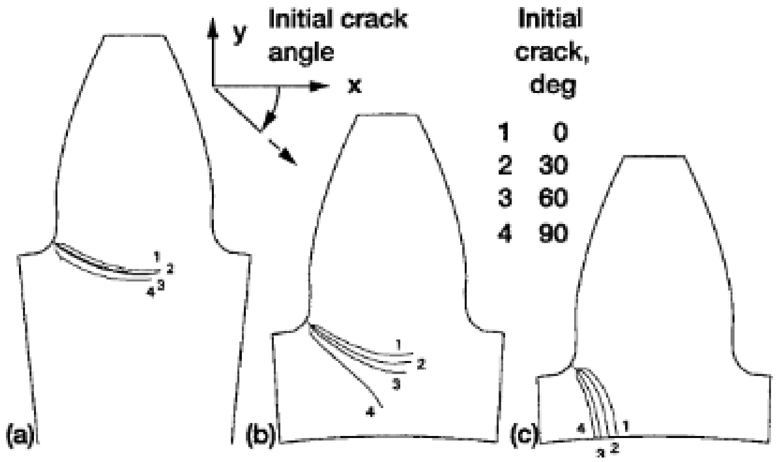


**Figure 3.24:** Crack propagation path considering different backup ratios [59]

According to [60], the occurrence of rim fractures significantly increased as the backup ratio decreased and as the initial crack location was moved down the root of the tooth as can be seen in Fig. 3.25. The effect of the backup ratio on the propagation path of a crack is shown in Fig. 3.26.
Note that cracks initiating at low $\theta_0$ conditions are rather rare in the field of experience [60], being $\theta_0$ the initial crack location angle (Fig. 3.23).
On the base of the backup ratio values, it is more likely to have a tooth crack in the Circular Spline (CS backup ratios are usually grater than 1) while on the Flexspline it is more common to have a rim crack, as shown in Figure 3.26.

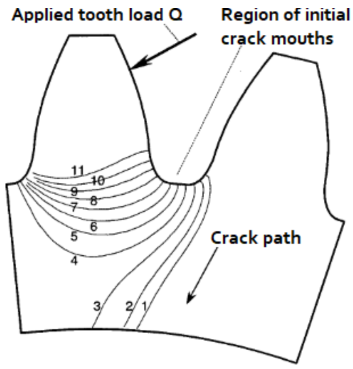


**Figure 3.25:** Effect of initial crack location [60]

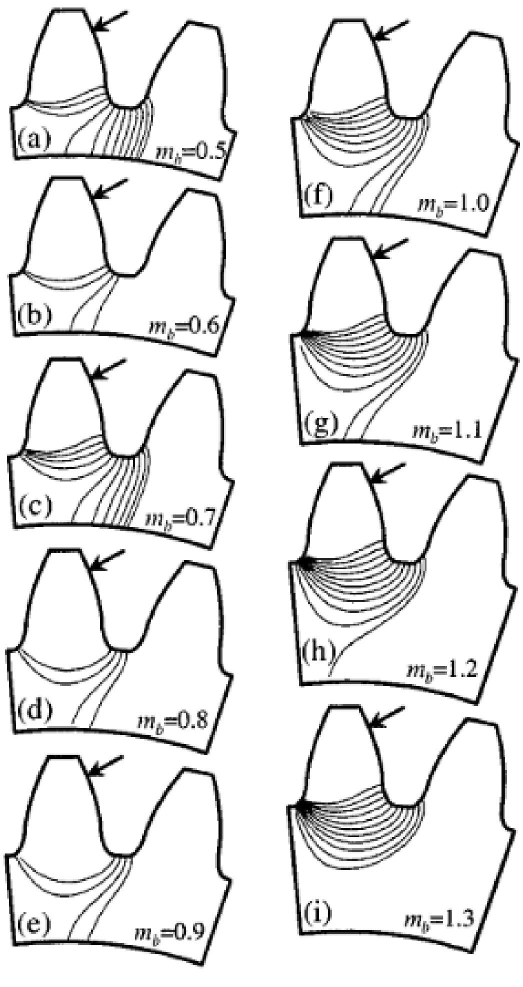


**Figure 3.26:** Effect of backup ratio, indicated with $m_b$, and initial crack location on propagation path [60]

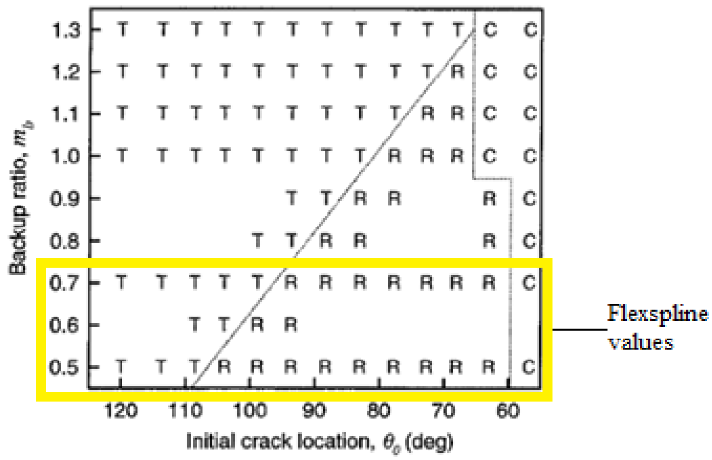


**Figure 3.27:** Effect of backup ratio and initial crack location on failure mode. T = tooth fracture; R = rim fracture; C = compression (no crack propagation). [60]

Some examples of backup ratios values in Flexsplines, taken from [34, 58]:

$$\begin{array}{lll} \delta = 0.3 & h = 0.45 & \Longrightarrow\ b = 0.45 \\ \delta = 0.685 & h = 1.19 & \Longrightarrow\ b = 0.576 \\ \delta = 0.48 & h = 0.831 & \Longrightarrow\ b = 0.577 \end{array}$$

The Flexspline can present different fracture modes depending on which part of it is considered:

1. toothed gear;

2. cup (from the rear cross section to the boss);

The toothed gear had a more complex stress distribution than the cup because it is forced and excited by the rotation of the WG and by the tooth engagement with the CS. A crack on the base of a tooth of the FS is subjected to fracture Mode I since the meshing force tries to open the crack with a stress action on a perpendicular direction to the crack propagation. On the other hand, the movement of the WG generates both modes I and II, because in the major axis region, due to rotation, we have Mode I since it makes the FS expand, but because of the elliptical deformation, the FS engages in and out from the CS, and the WG causes a Mode II.

The FS cup has the role to convert the elastic deformation of the toothed gear into the rotation of the boss. So the first part, closer to the gear, is subjected to elastic deformation, while the part closer to the boss is subjected to torsion. In this zone, the stress mode is Mode III on the boss (load on the same plane of crack propagation), while on the upper horizontal part there is Mode I (load perpendicular to the crack).

### Cup stresses: fatigue breakage failure of the Flexspline diaphragm at the corner

Breakage at the corner of the diaphragm with the boss of the flex-spline is a typical fatigue failure pattern of SWG. Figure 3.28 is a section drawing of FS structure with fatigue breakage at the corner of the diaphragm with the boss. The diaphragm experiences the fatigue breakage at the part of major stress concentration of FS structure. This failure pattern is very dangerous for industrial robots when SWG is used as joints and in this case the output torque cannot be completely transferred to the output shaft which regulates the position of the link.

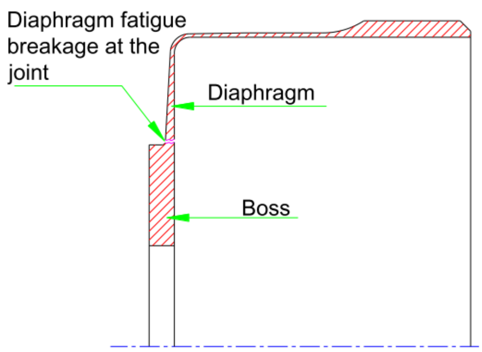


**Figure 3.28:** Fatigue breakage of Flexspline at the corner of the diaphragm with the boss [61]

In [61] a three-directional strain gauge is used to measure the diaphragm stresses. By comparing Fig. 3.29.a with Fig. 3.29.b, it is found that the normal stresses in the radial and circumference directions almost have no changes when the output torque is changed from zero into 110 Nm. The only change is the shear stress. The average value of the shear stress is increased from zero to 13.6 MPa when the torque is increased from zero to 110 Nm. Of course, the maximum and minimum values of the shear stress signals are also increased responsively with the increment of the average value. But the amplitude of the shear stress signals almost has no change [61].

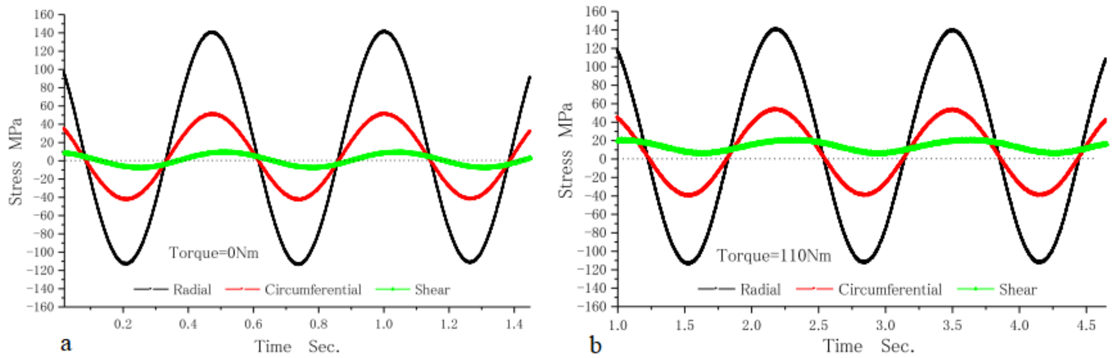


**Figure 3.29:** Diaphragm stress signals [61]

This is readily explained: the normal stresses in the radial and circumference directions are only resulted from the elliptical deflection of WG (difference between the radius of the major axis and the radius of the minor axis of the elliptical WG). So, if the shape of WG has no change, the normal stresses in the radial and circumference directions shall keep the same value.

The torque has only effect on the average value of the shear stress signals and has nothing to do with the normal stresses in the radial and circumference directions. In summary, it can be thought that fatigue breakage of the diaphragm is resulted from the elliptical deflection of WG and the external torque. The amplitude of the

shear stress signal of the diaphragm at the corner is determined by the elliptical deflection of WG and the average value of the shear stress signal at the corner is determined by the external torque. So, the average value and amplitude of the shear stress signal at the maximum stress point of the corner can be reasonably used as an indicator to evaluate fatigue breakage strength of the diaphragm.
Considering only the shear stress, Fig. 3.30 is obtained. It shows how the average value of the shear stress waveform is increased with the increment of the torque. A relationship between the external torque and the average value of the shear stress waveform is given in Fig. 3.31. It is found that the average value of the shear stress waveform is in linear relation with the torque. This confirms that the amplitude of shear stress waveform is determined by the elliptical deflection of WG, but the average value of shear stress waveform is resulted from the torque [61].

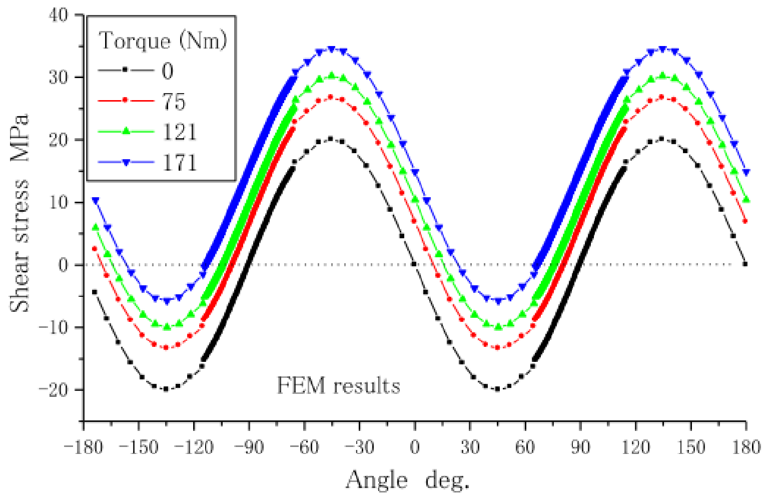


**Figure 3.30:** Effect of external torque on shear stress [61]

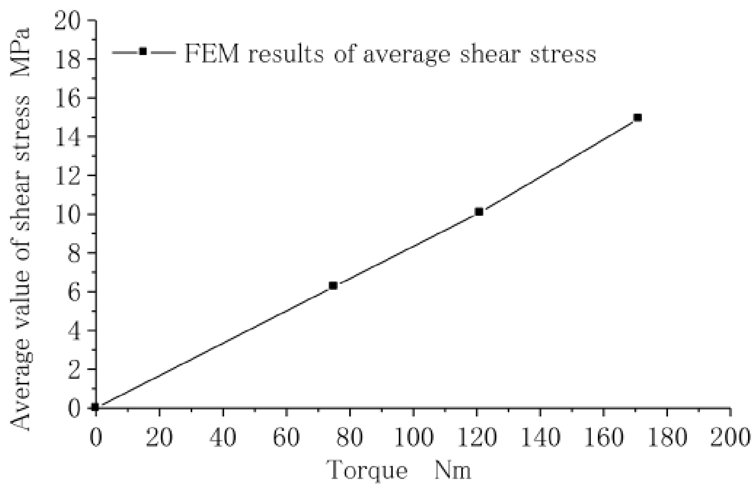


**Figure 3.31:** Relation between external torque and average value of shear stress [61]

## 3.4 Encoders

Encoders are sensors designed to output signals to an external machine controller. There are two main sensing technologies for the encoder system: magnetic and optical. Optical encoders use the interruption of light as principle of operation. A rotating disc inside the encoder contains opaque lines or patterns, and as the disc is rotated through a light source, the patterns on the disc interrupt the projected light beam. An internal photo-detector senses the pulsing light, which is translated and forwarded to an external control system via the encoder electronics.
Unlike optical encoders, magnetic encoders find rotation by sensing changes in a local magnetic field. The typical magnetic rotary encoder relies on a silicon chip which contains a hall-effect sensor. The hall-effect sensor, which is mounted within close proximity to a rotating magnet, finds the relative strength of the magnet corresponding magnetic field and outputs a voltage relative to the change in magnetic polarity.
The optic lens and the internal rotating disk of optical encoders are considerably more prone to damage than the simple microchip design of magnetic encoders. Magnetic encoders, which use a Hall-effect microchip, contain almost no moving/wearing parts.

**Structural components**

An encoder is usually composed by: an electronic package specific to the encoder type, magnetic or optical, an outer casing to protect the encoder internal mechanics, ball bearings to contain the encoder shaft, and the encoder shaft.

Regarding the case study of this thesis, as already specified in Sec. 2.6, the UR5 is equipped with two magnetic rotary absolute encoders, one is placed at the reducer end to monitor the actual rotating angle of the robot joint (position control), the other one is positioned before the motor and it is used for the speed control, as shown in Fig. 3.32.

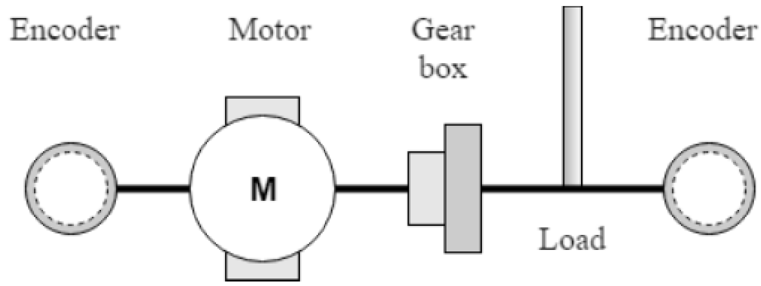


**Figure 3.32:** Double encoders location [62]

By placing encoders on both motor and load sides it is possible to detect the displacement caused by the joint elasticity and robot control algorithms can use this data to eliminate compliance errors and vibrations in the system. This additional information on the joint can be used at least in three possible ways: identification, control, and external torque sensing. A detailed research about this topic goes beyond the intent of this work but additional information can be found in [62]. In the following pages an analysis on the failure modes of these components will be developed, also taking into consideration the optical encoders that are still used in many robotic applications (particularly for cartesian robots and older version of manipulators).

### 3.4.1 Optical encoders

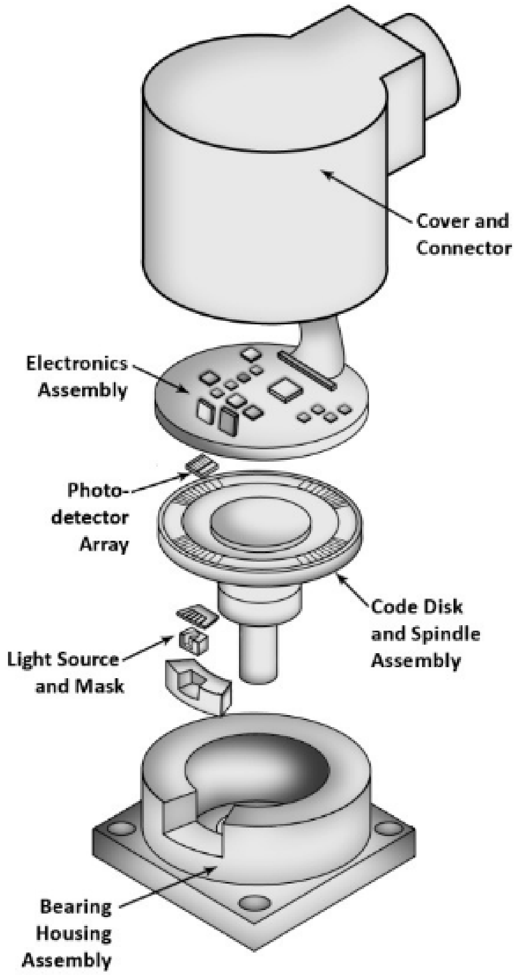


**Figure 3.33:** Optical encoder [63]

All optical encoders operates in the same basic way. The light source directs rays through a plane convex lens that focuses the light into a parallel beam which is then splitted to produce a second beam of light 90° out of phase. Light passes through a code disk made of tempered glass, polycarbonate, or metal, and it is detected by a photodiode. The pulse disk turns, creating a light/dark pattern through the clear and opaque segments of the disc. To operate flawlessly, optical encoders require a clean path from the emitter diodes to their receiver through the disk, located in between the two. The internal rotating disk is the most fragile component of the sensor:

- **glass disks** are susceptible to scratching and fracture under shock (see Fig. 3.34);
- **plastic disks** are quite shock resistant, but are more likely to wrap and lose their shape at higher temperature, and are likely to break down in chemically aggressive environments;
- **metal disks** better withstand shocks, vibrations, heat and chemicals (see Fig. 3.34).

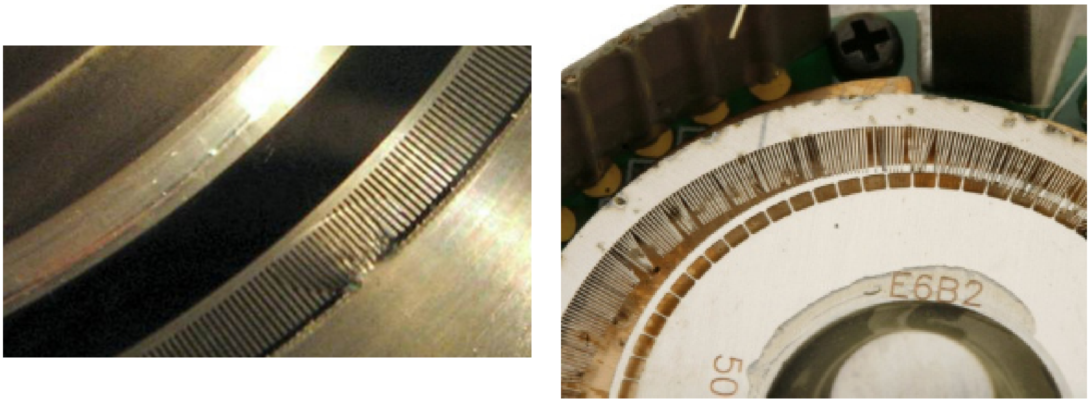


**Figure 3.34:** On the left: damaged glass disk of optical encoder [64]. On the right: destroyed coded metal disk after a series of jolts [63]

The sensing technology of optical encoders is prone to self deterioration. The main problem with this sensing type in some applications is dirt and water penetration over time, interfering with the machined slots in the disk or etchings in the rotor. The optical encoder works well when it is brand new because the machined slots or etchings are precise and free of contaminants. But over time, dirt and water inevitably penetrate the encoder causing loss of precision.

One solution from the designer is to seal the encoder so tight that the outside contaminants can't enter and cause problems (I.P. ratings of 66 or 67 are common place for optical encoders). Anyway, it is not possible to manufacture a 100% sealed optical encoder because the bearing-to-shaft assembly will never be perfectly tight, since there must be some clearance to allow the bearing to slide over the shaft during assembly of the encoder. This clearance creates openings or paths through which contaminants can enter.

**Figure 3.35:** Creation of water inside the encoder casing due to condensation after temperature cycling [63]

But when temperature cycling is concerned, tightly sealed encoders and the IP rating methodology are quickly proved invalid. During operation, the encoders tend to heat up, whereas during non operational time or maintenance outage, the encoder cools to near ambient temperature. It is this temperature cycling (in combination with the tightly sealed encoder housing) that constitutes a dangerous failure mode. This is because the encoder creates its own water in the housing through condensation as it cools down. Over time temperature cycling causes pressure changes and seals fail, which creates a path to the inside of the encoder. Often, the cause of the problem is simply moist air which enters the encoder and then condenses, rains, or freezes inside the encoder. A possible damage due to water condensation is visible in Fig. 3.36.

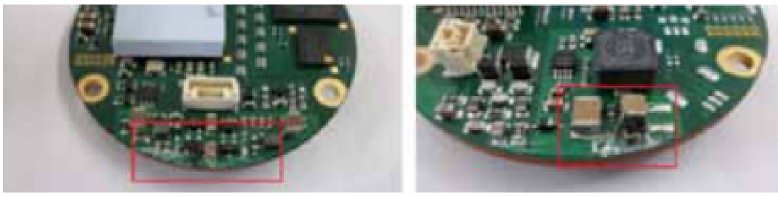

**Figure 3.36:** Water penetration damage in an optical encoder PCB [65]

### Mechanical considerations

Optical encoders inherently require very precise alignment and positioning of the light source, the rotor and the optical light sensing mask in order to attain the required pulse performance. Shocks and vibrations constitutes a potential combination for failure condition. They can cause errors on the internal positioning and alignment of sensitive optical components: in the extreme situations, this condition can also cause serious problems with the optical disk inside the encoder. With enough externally applied forces, the disk can crack or shatter impacting the sensor.

### Main failure causes

Optical encoders are subject to various types of failure causes and the main ones are listed in the next pages. The following analysis brings together the critical failure modes highlighted by various researchers among which [63–67] are the most relevant.

1. **Environment**: these devices are more likely to fail when placed in operating environments that subject them to aggressive contaminants, dust particles, submersion in liquids, intensive cleaning procedures and so on. Encoders in harsh environments are often exposed to paticulates such as sand, liquid drops,

small wood/iron chips, dust and moisture particles. These contaminants will enter the encoder, blocking optical processes and resulting in the failure of the device.

2. **Electrical failure**: encoders can be exposed to voltage surges and short circuits caused by wiring issues. Standard encoders can't withstand either condition. Humidity collected due to sealing failure causes damages to the wirings and the PCB (Printed Circuit Board).

3. **Temperature cycles**: these temperature cycles can cause direct electronic failures and, even more commonly, seal failures in standard encoders as already explained in section 3.4.1. Ambient temperature variations can accelerate encoder failure rates. During encoder cool down, pressure differences between outside environment and the inside of the housing can cause the encoder to "breathe", drawing air into the housing. As temperature of the encoder housing drops, any contained humidity will condense, resulting in dew collecting on PCBs, wirings, code disk, which can lead to encoder failure.

4. **Vibration and shocks**: the encoder experiences nearly continuous vibration during operation, and dynamic motions create even greater dynamic forces on the encoder. In instances of extreme vibration or unexpected jolts from mechanical acceleration and deceleration, the encoder's disk is liable to flex, causing contact between the disk and the optical sensing element. Besides mechanical stresses, vibration fault corresponds to the frequency variation of the position signal.

5. **Bearing failure**: typical encoders use a tiny ball bearing to support either a solid or hollow shaft construction. These bearings frequently fail when subjected to vibration and loads caused by tethering hollow shaft models, spline coupling systems or belt-driving shafted models. At the initial installation

the encoder is mounted correctly in line with the application, but as the motor ages, so do the motor's bearings. Guided by the worn bearings, the motor's shaft is allowed to wobble as it rotates. The application wobbling shaft transfers negatively to the encoder bearings as side load, inevitably leading to the failure of the encoder readings due to misalignment.

6. **Seal failure**: the repeated temperature cycling causes pressure on the encoder seals which then yields. More temperature cycles draw dirt, dust, water and oil into the optics and bearings, causing optical system or bearing failure. When the encoder is in operation, its components generate heat, which increases the pressure of the environment sealed within the encoder body. The warm expanded air, pushed out from within the heated encoder, is later pulled back into the housing when it is powered down and allowed to cool. The simple principle of equalizing air pressure translates into sensor failure as the encoder draws moisture in via the cooled air it pulls in after shut down. Dirt and water will interrupt or distort the beam, or create some issue on the disk driving the optical system to failure.

7. **Output signal failure**: encoders provide feedback to the drive system to allow the drive to start the motor from zero speed with the desired workload, and keep the velocity and torque under control during operation. From a control point of view, an encoder failure will cause the system to measure a persistent steady-state error and therefore continue to drive the motor to attempt to reduce this error [67].

### 3.4.2 Magnetic encoders

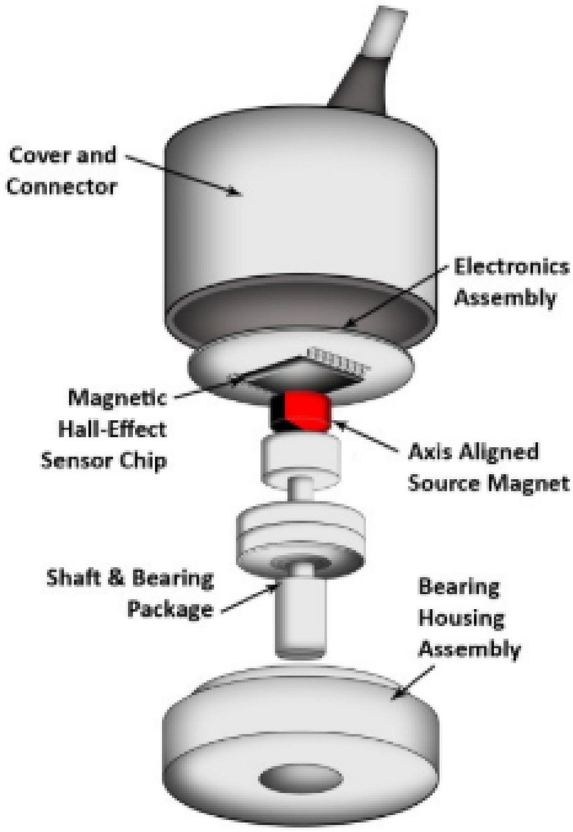


**Figure 3.37:** Magnetic encoder [63]

Magnetic encoders don't require fragile glass disks or dust-free operational environment. Magnetism reaches through moisture, oil and dirt unaffected, enabling the magnetic sensor to correctly and accurately detect rotation under all conditions. While jolts from acceleration and deceleration, environmental vibration, and automated assembly processes can quickly damage an optical encoder, magnetic encoders, because of their solid state design, are suited to handle any sort of external force without risking accuracy.
These encoders have virtually no moving or wearing parts or seals. The magnetic

ring or rotor is mounted onto the motor shaft or stub shaft. The magnetic ring rotates in front of a magnetic sensor which provides the measurement of position and speed. A modular no-bearing magnetic encoder provides the longest service life and highest durability of any encoder solution available at the moment according to [64].

**Failure modes**

The only problem with magnetic encoders on a factory floor is that they can deliver erratic output signals resulting from damage to the sensitive ICs (Integrated Circuits) that transmit quadrature output to the controlling device. Such errors may be caused by EMI (Electro-Magnetic Interference) or radiated noise from factory equipment surrounding the encoder [66].
Also wiring issues due to severe vibrations or excessive heat can be considered as failure causes, but these conditions are unlikely to happen since they can still be well tolerated by the magnetic encoder micro-chip.

## 3.5 Bearings

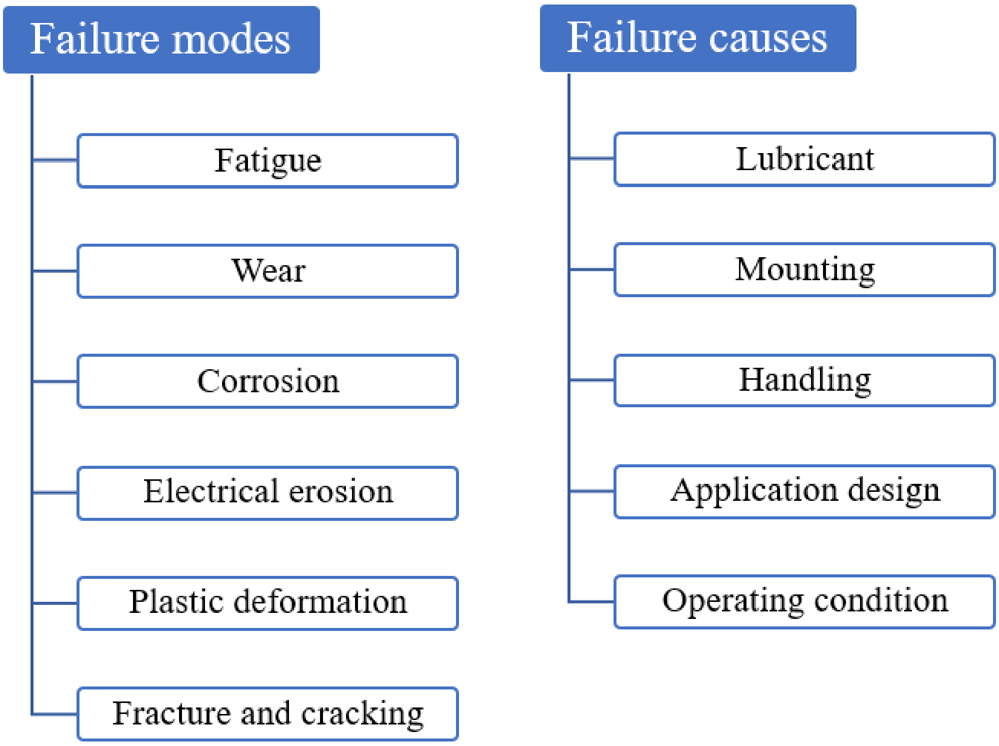


**Figure 3.38:** Bearing main failure causes

Rolling bearings are machine elements used to permit a rotary motion and to transmit forces between parts of machines and are used in all rotational components. Thus, rolling bearings are among the most important components in the vast majority of machines. Under nominal conditions, bearings are among the few components that are designed for a finite life because of the fatigue properties of the materials used. Premature bearing failure can occur for a variety of reasons. Each failure leaves its own unique imprint on the bearing, called "pattern". Consequently, by carefully examining a failed or damaged bearing, it is possible, in the majority of cases, to establish the root cause and define corrective actions to prevent recurrence of the problem.

The most common failure mode of a bearing is wear [42], indeed bearing surfaces are neither perfectly flat nor smooth and when two surfaces such as a ball and raceway come into contact, only a small fraction of the surface area is actually supporting the load. The result is high contact stresses, which lead to excessive friction and wear.

In this analysis the focus will be on ball bearings. Ball bearing related defects can be categorized as: outer bearing race defect, inner bearing race defect, ball defect, and train defect, each one having its own frequency signatures related to the number of balls, ball diameter and ball pitch.

Under normal operating conditions with balanced load and good shaft alignment, fatigue failures may take place anyway. These failures may lead to increased vibration and noise levels. Flaking or spalling of bearings might occur when fatigue causes small pieces to break loose from the bearing. Other than the normal internal operating stresses caused by vibration, inherent eccentricity, and leakage currents due to solid state drives, bearings can be spoiled by many other external causes such as the following:

1. **contamination and corrosion** caused by pitting and sanding action of hard and abrasive minute particles or corrosive action of water, acid, etc;
2. **improper lubrication** which includes both over and under lubrication causing overheating and abrasion;
3. **inaccurate installation of bearing**:
   (a) improper internal clearance: a small internal clearance may limit the amount of misalignment that can be tolerated and can lead to heavily preloaded bearings. Excessive internal clearance will cause the load to be carried by too few rolling elements;
   (b) misalignment: improperly forcing the bearing onto the shaft or in the housing (due to misalignment), indentations are formed in the raceways

(brinelling). It's essential for the motor and load to be correctly aligned under actual operating temperatures and conditions. Machines that are correctly aligned at room temperature may become badly misaligned due to deformation or different thermal growth associated with temperature change.

### 3.5.1 Bearing life and failures

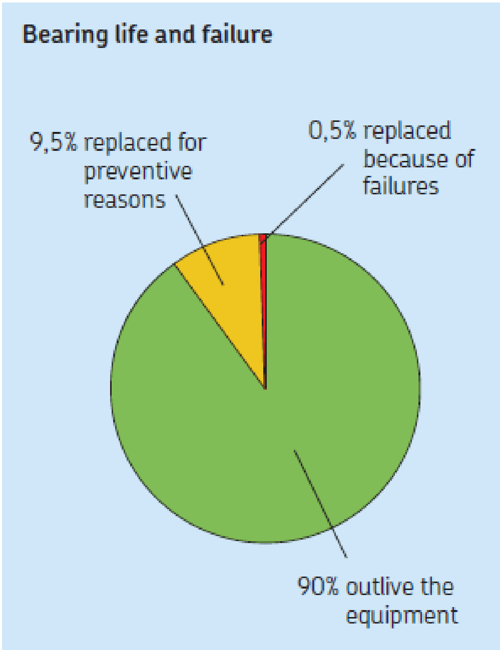


**Figure 3.39:** Bearing life and failure [68]

According to the data collected in [68], every year an estimated 10 billion bearings are manufactured around the world. Only a small fraction of all bearings in use actually fail. Most of them (some 90%) outlive the equipment in which they are installed. A number of bearings (9,5%) are replaced prior to failure for security (preventive) reasons. This is because under proper operating condition, nominal behaviour of bearings and their rated life can be estimated with accuracy and therefore they can be replaced before failure occurs. Approximately 0,5% of bearings are replaced because they are damaged or fail. This means that some 50.000.000 bearings are replaced every year due to damage and failure. There are several reasons why bearings can be damaged or fail. Generally speaking:

- $\frac{1}{3}$ fail due to fatigue;
- $\frac{1}{3}$ fail due to lubrication problems (wrong lubricant, wrong quantity, wrong lubrication interval);
- $\frac{1}{6}$ fail due to contamination (ineffective seals);
- $\frac{1}{6}$ fail for other reasons (improper handling and mounting, heavier or different loading than anticipated, wrong or inadequate fits);

Obviously these percentages vary depending on the industry or application. According to [69], more than 90% of all bearing failures are due to external influences. These include lubrication conditions, assembly installation techniques, contamination of the operating environment, and improper bearing size selection for the application. Under proper operating conditions, a bearing should only fail from fatigue which is predictable based on the bearing size and it's application parameters.

This last statement is confirmed by [42], where it is highlighted that the service life of a bearing is usually limited by either excessive wear or fatigue. Excessive wear occurs when the bearings are improperly installed or exposed to hostile operating environments (inadequate lubrication, misalignment, contamination, shocks, vibrations, extreme temperature) which cause bearings to wear out prior to their estimated design life. In contrast, a bearing can be expected to perform adequately for the duration of its rated life, given proper operating conditions, until failure occurs due to fatigue since the load carrying balls, raceways, rollers, etc. are subjected to cyclical contact stresses. Anyhow, it is notable to report that, always according to [42], less than 10% of all ball bearings last long enough to fail due to normal fatigue.

Bearing damages can be classified into two damage categories according to [70]:

1. **pre-operational**: occurs prior to or during bearing installation.
   (a) Incorrect shaft and housing fits;
   (b) defective bearing seats;
   (c) static misalignment;
   (d) faulty mounting practice;
   (e) excessive voltage;
   (f) transportation, handling and storage.
2. **Operational**: occurs while the bearing is in operation.
   (a) Material fatigue;
   (b) ineffective lubrication;
   (c) ineffective sealing;
   (d) vibration;
   (e) operational misalignment;
   (f) current leakage.

Operational causes of damage will be analyzed in the detail in the following part of this research, at section 3.5.3.

### 3.5.2 Symptoms of bearing failures

Those symptoms are described in depth in [68], where a solution is also suggested for each possible causes.

1. **Excessive heat.** This problem can be caused by:
   (a) lubrication problem;
   (b) sealing conditions;
   (c) insufficient clearance in operation;
   (d) improper bearing loading.
2. **Excessive noise levels.** Possible causes:
   (a) metal-to-metal contact;
   (b) contamination;
   (c) too loose fits;
   (d) surface damage;
   (e) rubbing.
3. **Excessive vibration levels.** Possible causes:
   (a) metal-to-metal contact;
   (b) contamination;
   (c) too loose fits;
   (d) surface damage.

4. **Excessive shaft movement.** Possible causes:
   (a) looseness;
   (b) surface damage;
   (c) incorrect internal bearing clearance.
5. **Excessive frictional moment to rotate the shaft.** Possible causes:
   (a) preloaded bearing;
   (b) sealing drag;
   (c) surface damage;
   (d) design problem.

### 3.5.3 ISO failure modes classification

The ISO workgroup [71] established that:

- a cause for failure shows a certain characteristic;
- a certain failure mechanism can be associated with a certain failure mode;
- from the damage observed, one can (try to) define the root cause of failure.

The failure modes are divided into 6 main modes and thereafter into sub-modes for a total of 14 failure modes, which are highlighted in the following diagram in Fig. 3.40.

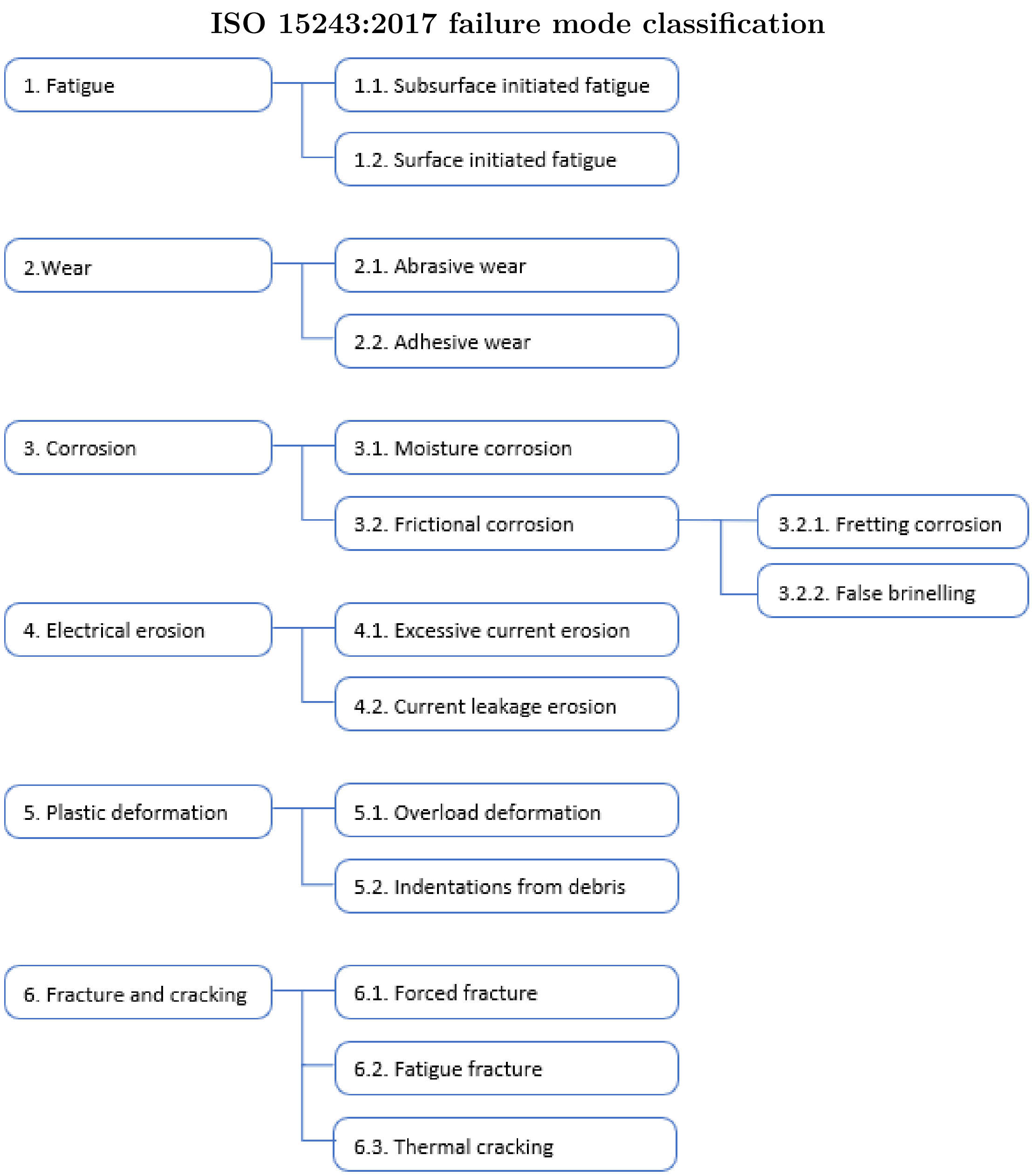


**Figure 3.40:** ISO failure mode classification [71]

### Fatigue

Rolling contact fatigue is caused by the repeated stresses developed in the contacts between the rolling elements and the raceways.

1. **Subsurface initiated fatigue**

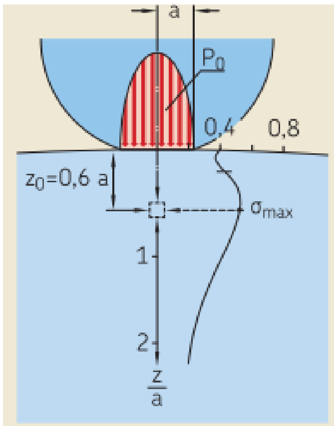


**Figure 3.41:** Subsurface initiated fatigue [68]

In a rotating bearing, cyclic stress changes occur beneath the contact surfaces of the raceways and rolling elements. During each revolution, as that one point on the raceway enters and exits the load zone, compressive and shear stresses occur. Depending on the load, temperature and the number of stress cycles over a period of time, there is a build-up of residual stresses that cause the material to change from a randomly oriented grain structure to fracture planes. Here, subsurface microcracks develop beneath the surface at the weakest location, around the zone of maximum shear stress. The crack finally propagates to the surface and spalling occurs. Spalling gradually increases and gives rise to noise and vibration levels in the machine.

2. **Surface initiated fatigue**

Fatigue initiated from the surface is typically caused by surface distress. Surface distress is damage initiated at the rolling contact surfaces due to plastic deformation of the surface asperities. Contact between the asperities of the rolling element and bearing raceway is most often the result of inadequate lubrication conditions.

Possible causes:

- reduced lubrication regime (contact surfaces are not adequately separated);
- sliding motion under heavy load and low lubricant film condition;
- solid contaminants in the lubricant.

**Figure 3.42:** Inner race surface initiated fatigue failure - spalling [71]

### Wear

Wear is the progressive removal of material from the surface, resulting from the interaction of two sliding or rolling/sliding contacting surfaces during service.

1. **Abrasive wear**

   Abrasive wear occurs when a hard rough surface slides across a softer surface. The material removal can be caused by:

   - inadequate lubrication that allows metal-to-metal contact, which leads to plastic deformation of the asperities;
   - ingress of solid contaminants;

- other factors can include a combination of low speeds and heavy loads.

Abrasive wear is a degenerative process that eventually destroys the micro-geometry of a bearing because wear particles further reduce the lubricant's effectiveness.

**Grooving**

Grooving occurs when hard contaminants enter the bearing and get wedged in the cage and cut grooves in the rollers. Particles can also get caught between rollers and cut grooves in the bearing races. The damage is permanent and will lead to early bearing failure.

2. **Adhesive wear (smearing)**

   Adhesive wear is a type of lubricant-related damage that occurs between two mating surfaces sliding relative to each other. It is characterized by the transfer of material from one surface to another (smearing) and it is typically accompanied by frictional heat. Smearing is not common under normal operating conditions.

   - **Smearing (adhesive wear) due to severe accelerations:**

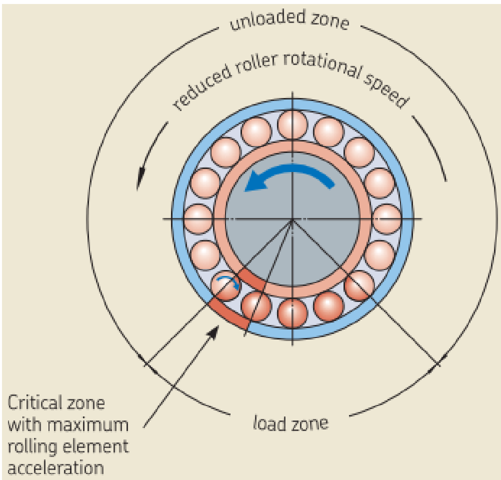


**Figure 3.43:** Smearing [68]

Smearing happens because of inadequate lubrication conditions when sliding occurs and localized temperature rises from friction cause adhesion of the contacting surfaces, resulting in material transfer.

Operating at relatively high speeds, outside the load zone, the rolling element rotation is slowed down because the rings do not drive the rolling elements. The rolling elements are therefore subjected to rapid (sudden) acceleration while entering the load zone. This sudden acceleration can cause sliding, which can generate enough heat, so that the two surfaces melt together at the points of metal-to-metal contact.

This leads to:

i) high friction;

ii) high temperature.

Large bearings are quite sensitive to smearing. The weight of the rolling elements becomes important as they slow down considerably outside the load zone. When re-entering the load zone they are almost instantly accelerated to the rotational speed, but due to the rolling element weight it occurs with (partial) sliding.

- **Smearing (adhesive wear) due to too light loading:**

  Smearing is usually a sudden occurrence as opposed to an accumulated wear process. It can also occur between rolling elements and raceways when the load is too light relative to the speed of rotation.

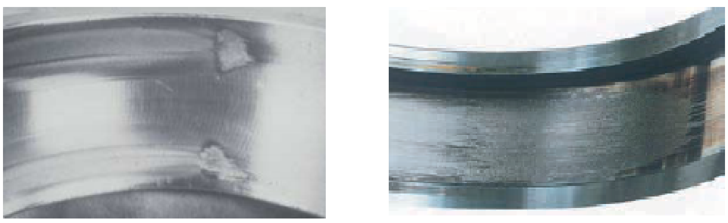

**Figure 3.44:** Smearing failure [71]

**Corrosion**

Corrosion is the result of a chemical reaction on metal surfaces.

1. **Moisture corrosion**

   Ineffective sealing arrangements can allow moisture, water and aggressive liquid contaminants to enter the bearing. This can lead to oxidation/rust. Especially when water is allowed to enter the bearing assembly and mix with the system lubricants, a chemical reaction can cause surface etching.

   - **Etching**

     Etching is deep-seated corrosion caused by water in the lubricant at standstill. It is more likely to occur in applications where there are aggressive chemicals and high temperatures.

2. **Frictional corrosion**

   Frictional corrosion is a chemical reaction activated by relative micromovements between mating surfaces under certain friction and load conditions.

   i) **Fretting corrosion**

   Fretting corrosion occurs when there is relative movement between a bearing ring and its seat on a shaft or in a housing, especially between components that are transmitting loads under oscillating contact surface micromovements. The relative movement may cause small particles of material to become detached from the bearing surface and its seat. Those asperities will oxide and act as fracture notches. Fretting corrosion manly happen due to:

   - heavy loading;
   - shaft bending;
   - inadequate seat.

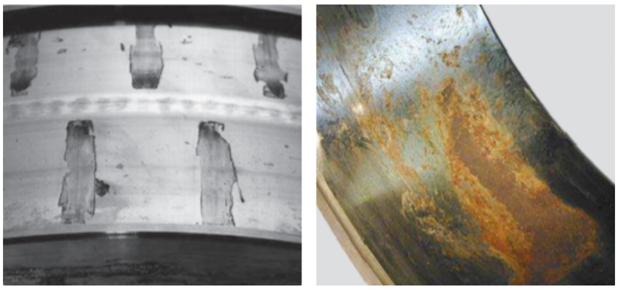

**Figure 3.45:** On the left: moisture corrosion. On the right: frictional corrosion. [71]

ii) **False brinelling (vibration corrosion)**

False brinelling occurs in the contact area due to micromovements and/or resilience of the elastic contact under cyclic vibrations. Depending on the intensity of the vibrations, lubrication conditions and load, a combination of corrosion and wear can occur, forming shallow depressions in the raceway. The rubbing eventually leads to surface oxidation and a failure initiation point.

The root cause of false brinelling is vibration at standstill: it happens in stand-by equipment, when long stopped periods in the presence of vibrations from nearby operating equipment are alternated with rather short running sessions. The magnitude of the damage depends on the level of vibration, frequency, and length of standstill.

**Figure 3.46:** False brinelling on the outer ring raceway of a ball bearing [71]

### Electrical erosion

Electrical erosion is the localized microstructural change and removal of material at the contact surfaces caused by the passage of damaging electric current.

1. **Excessive current erosion**

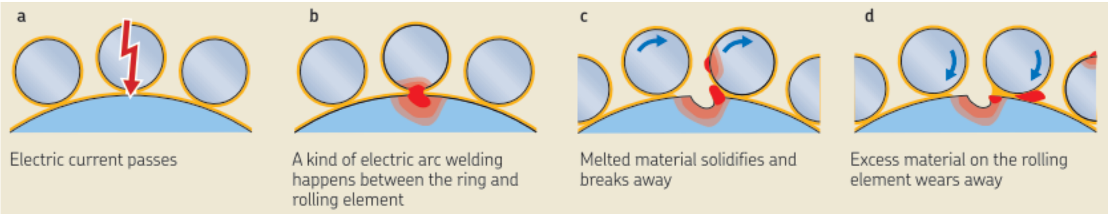


**Figure 3.47:** Electric erosion [68]

When an electric voltage between bearing rings and rolling elements exceeds the insulation breakdown threshold value, an electrical current passes from one bearing ring to the other through the rolling elements and their lubricant films. This will result in localized heating within very short time intervals, so that the contact areas melt and weld together consequently breaking away due to the rotation of the rolling element.

2. **Current leakage erosion**

This phenomena happens when the intensity of the current is relatively low but becomes continually established.

Due to small internal clearances in the bearing, electrical current can arc between component surfaces causing rolling surface pitting. In the initial stage of current leakage erosion damage, the surface is typically damaged by shallow craters that are closely positioned to one another and smaller in diameter compared to the damage from excessive current. This eventually leads to surface initiated fatigue, spalling and even sudden seizure and lubricant deterioration.

### Plastic deformation

This is a permanent deformation that occurs whenever the yield strength of the material is exceeded.

1. **Overload deformation**
   Overload deformation can occur while the bearing is stationary (most common), or while rotating (uncommon). Overload deformation can be caused by static overloading, shock loads or improper handling. When a deformed bearing is put into operation, high noise and vibration levels will result.

**Figure 3.48:** Cage plastic deformation caused by a shock load during handling [71]

2. **Indentation from debris**
   Solid contaminants can be introduced into a bearing via the seals or lubricant. They can also be the result of wear or damage to an adjacent component, such as a gear. When a solid contaminant is over-rolled by the rolling elements, it is pushed into the raceway and causes an indentation.

### Fracture and cracking

Cracks are initiated and propagate when the ultimate tensile strength of the material is locally exceeded. Fracture is the result of a crack propagating completely through a section of the component or propagating such that a portion of the component is completely separated from the original component. Excessive preload, high shock loads, poor handling and extreme thermal conditions can lead to component fracture.

1. **Forced fracture**
   A forced fracture results when stress concentrations exceed the tensile strength of the material. Local overloading and over-stressing (e.g. from impact) are two common causes of a forced fracture.

2. **Fatigue fracture**
   A fatigue fracture starts when the fatigue strength limit of a material is exceeded under cyclic bending. Fatigue is one of the main causes of crack initiation/propagation.

3. **Thermal cracking**
   Thermal cracking (heat cracking) is caused by high frictional heating due to sliding motion. Sliding and insufficient lubrication are the major failure contributor. High frictional heat results in transverse cracks and eventually the ring will crack through.

**Figure 3.49:** Fracture of outer ring due to impact [71]

### 3.5.4 Bearing failure causes

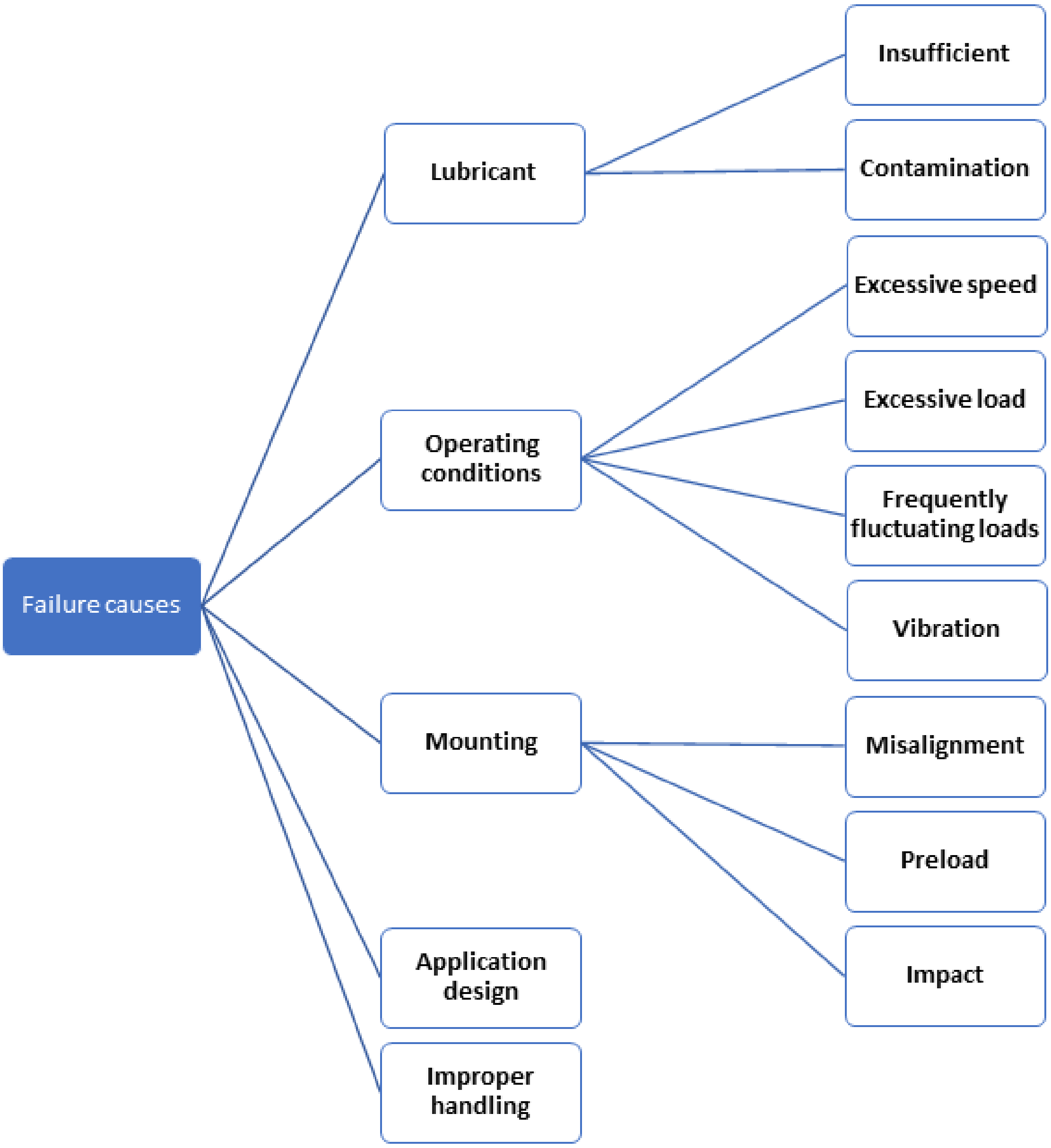


**Figure 3.50:** Bearing failure causes

### Lubricant based failure causes

All bearings need proper lubrication to function properly. Lubrication must be correctly selected, be applied to the correct quantity level, be clean, monitored, and maintained correctly. Insufficient lubricant or contamination will cause:

- increased wear;
- material smearing;
- pitting;
- spalling;
- indentations.

### Operating condition based failure causes

Operating conditions must be carefully considered when choosing the proper bearing and determining the bearing expected life, because most failure modes can be accelerated by operating conditions such as overload or excessive rotational speed.

### Bearing mounting-based failure causes

Incorrect mounting practices can severely shorten bearing life.

- Faulty electrical insulation can initiate any electrical failure mode previously analyzed.
- Misalignment can cause the load to be unevenly distributed creating greater than expected stress at one end of the rolling surfaces causing other unexpected and uneven wear.
- Static overload will produce true brinelling or permanent plastic deformation at the rolling element and raceway contact points.

What all failure causes have in common are some symptoms they generate:

1. increasing friction;
2. increasing vibration;
3. increasing noise;
4. efficiency loss.

### 3.5.5 Bearing Failure Rate Prediction

From SKF bearing catalogue [72], the definition of bearing rating life is the following: "bearing life is defined as the number of revolutions (or the number of operating hours) at a given speed that the bearing is capable of enduring before the first sign of metal fatigue (spalling) occurs on a rolling element or the raceway of the inner or outer ring."
Statistical methods are used to estimate bearings life based on the results of tests conducted on a large groups of the same type of bearing which are run to failure under controlled laboratory conditions to establish a fatigue life rating. This rating, known as the $L_{10}$ life, is defined as the number of hours that 90% of a sufficiently large group of apparently identical bearings, operating at their rated load and speed, can be expected to attain or exceed before exhibiting the first evidence of fatigue.

Considering only the load and speed, the basic rating life can be used, which in accordance with ISO 281 is calculated through the following equation:

$$L_{10} = \left(\frac{L_s}{L_A}\right)^y \tag{3.4}$$

where:

$L_{10}$ = Bearing life with reliability of 90%, [millions of revolutions];
$L_s$ = Basic dynamic load rating;
$L_A$ = Equivalent radial load;
$y$ = Constant, 3.0 for ball bearings, 3.3 for roller bearings.

The $L_{10}$ life can be converted to hours with the following:

$$L_{10h} = \frac{10^6}{60n} \times L_{10} \tag{3.5}$$

where:

$L_{10h}$ = Bearing life (at 90% reliability), [operating hours];
$n$ = Rotational speed, revolutions/min.

Service life in a particular application depends not only on load and speed, but also on a variety of influencing factors including lubrication, degree of contamination, proper mounting and other environmental conditions. So the $L_{10}$ rating life can be modified with certain adjustment factors such as: Lubricant Multiplying Factor, Lubricant Contamination Factor, Service Factor, Operating Temperature Multiplying Factor etc.

## 3.6 FMECA table

The following FMECA table, Tab 3.12, has been developed starting from the analysis just carried out in the Chapter 3, with the addition of data collected in various papers, books, reports, manuals and international standards [23, 24, 32, 42, 73–84].

The main intent of this table is to develop a ranked list of potential failure modes according to their effect on the system, evaluated through the RPN, in order to establish a priority based maintenance preventive strategy. As already specified in Sec. 2.2.1, risks are combinations of a certain potential failure cause, a malfunction and a consequence. To assess and categorize them, three main criteria are used: Severity (S), Occurrence (O) and Detectability (D). For the definition of these criteria, see again the Sec. 2.2.1, while for the scale of values used, the reference is to the following tables: Tab. 3.1, Tab. 3.2 and Tab. 3.3 of the Sec. 3.1. The failure modes which have high RPN number are critical failure modes and the components which contain these failure modes are the most critical components.

In the following Tab. 3.12, for every single component, the lines that concern the most critical failure modes, according to the overall RPN value, are highlighted in yellow. A discussion about criticality and severity of components is carried out in the "FMECA results" section, available in Sec. 5.

**Preliminary remark**

***The parameters values entered in the FMECA table need to be reviewed and confirmed with data taken directly from the field because, as repeated several times during the drafting of this thesis, in the literature there were no quantitative data that could allow a correct identification of the coefficients themselves. Therefore, an interpretation work about what was said in the literature was carried out, following a fuzzy logic and assigning values based on a qualitative description of the failure. For example, if in the literature it was reported that a certain type of failure occurred with greater probability than another, without however providing numerical details regarding this consideration, proper values that could reflect this assertion were assigned to the three parameters, in order to obtain a reasonable RPN. In order to get more truthful data it would be necessary either to interview experts in the various sectors or to compare what has been done with the FMECA tables of the robot manufacturers, which however are not publicly available.***

| COMPONENT | FAILURE MODE | CAUSES | SYMPTOMS | EFFECTS | SCORE | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | S | O | D | RPN |
| Electric Motor | Open winding | Excessively high temperature and vibrations | Asymmetry in stator windings, reduced torque | Motor failure | 8 | 5 | 7 | 280 |
| | Winding shortage turn-to-turn | Insulant degradation, contaminants, abrasion, high vibrations and temperature | Non-symmetric/lower/ intermittent currents | Motor performance degradation/losses | 8 | 9 | 7 | 504 |
| | Winding shortage phase-to-phase | Excessively high temperature, contamination, insulation breakdown due to wear, aging and vibrations | Over current | Motor failure | 8 | 6 | 7 | 336 |
| | Winding shortage phase-to-ground | High vibrations, misalignment, insulation breakdown | Over current | Motor failure | 8 | 5 | 7 | 280 |
| | Insulation failure | High temperature, contamination, leakage in cooling system, over-loading | Excessive overheat, over current | Shot circuit, motor failure | 9 | 6 | 7 | 378 |
| | Broken rotor bar/end-ring | Thermal stress, magnetic stress, mechanical stress (bearing failure), excessive number of start-up | Disturbance in airgap magnetic flux, vibrations, oscillations in the output torque | Abnormal current increase, possible short circuit and insulant degradation | 7 | 3 | 4 | 84 |
| | Bearing failure | Improper lubrication, contamination, improper mounting (shaft misalignment), overloading, fatigue, high temperature | High vibration levels, armature rubbing stator, unbalanced airgap length | Increase noise, seizure risk, overload and overheat, equipment shutdown, possible shaft damage | 7 | 6 | 8 | 336 |
| | Electrical arcing (not valid for ceramic bearing) | Electric erosion due to current which uses bearing as its path to ground | Asymmetry in the motor magnetic circuit, unshielded power cables | excessive vibrations, heat and noise levels, reduced effectiveness of the motor bearing lubricant | 7 | 5 | 5 | 175 |
| | Eccentricity - dynamic | Improper assembly, high temperature, worn bearing, bent rotor shaft, excessive speed, corrosion, contamination | Increase torque pulsation, ripple | Increase in vibrations and damage to bearings | 6 | 7 | 5 | 210 |
| | Eccentricity - static | Improper assembly, high temperature, worn bearing, bent rotor shaft, excessive speed, corrosion, contamination | Cyclic anomaly on phase currents, increased noise and vibrations (at rotor speed frequency) | Support bearing failure, efficiency loss, rotor-to-stator rub | 6 | 5 | 5 | 150 |
| | Sheared shaft | Fatigue, misalignment, bearing failure, frequent start and stop under heavy load | Shaft fracture | Armature rubbing stator, seized | 8 | 3 | 6 | 144 |

**Table 3.12 continued from previous page**

| COMPONENT | FAILURE MODE | CAUSES | SYMPTOMS | EFFECTS | SCORE | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | S | O | D | RPN |
| Electric Motor | Misalignment | Improper installation, wear, corrosion, bad maintenance | High vibrations | Equipment shutdown, bearing damage | 7 | 5 | 5 | 175 |
| | Cracked housing | Fatigue, external shock, vibration | Excessive noise levels | Leakage of dust into motor, shorted or seized | 6 | 3 | 3 | 54 |
| | Uniform magnets degradation | Overheating, advanced turn-to-turn short, aging of magnets | Efficiency loss in power conversion | Motor performance degradation/losses | 6 | 6 | 3 | 108 |
| | Localized magnets degradation | Local overheating, turn-to-turn short, aging of magnets | Non-symmetric current, increased common node current, efficiency loss | Motor performance degradation/losses | 6 | 6 | 3 | 108 |
| | Power MOSFET failure | High temperature and overcurrent or overvoltage | High termal gradient | Loss of the motor speed and direction control | 7 | 4 | 3 | 84 |
| | Power supply anomalies | Interruption of power, disconnection, electrical overload, wiring brakage | Dielectric breakdown | Voltage unbalance, short/open circuits and motor loss | 6 | 4 | 3 | 72 |
| | Connectors | Intermittent contact | Increased apparent resistance | Disconnection | 8 | 7 | 6 | 336 |
| Harmonic Drive | Tooth crack | Fatigue degradation, overloads | Periodic stiffness variation, "localized" noise | Actuator loss (possible jamming) | 8 | 6 | 5 | 240 |
| | Rim crack | Fatigue degradation, overloads, excessive stress combination | Stiffness variation, efficiency loss, vibrations | Component breakdown | 9 | 5 | 6 | 270 |
| | Abrasive Wear | Natural degradation, insufficient/contaminated lubrication or contaminated mesh area | Increased noise over wide frequency spectrum | Slow degradation in performance, tooth scoring, gear vibration and noise | 4 | 4 | 3 | 48 |
| | Pitting | Surface fatigue degradation, cyclic contact stress transmitted through lubrication film (excessive lubrication accelerate the process) | Increased noise over wide frequency spectrum | Degraded performance, tooth surface damage | 5 | 6 | 3 | 90 |
| | Spalling | Excessively high contact stress levels, cyclic contact stress | Similar to pitting except that the pits are larger, shallower and very irregular in shape. | Mating surface deterioration, welding, galling, eventual tooth failure | 6 | 6 | 4 | 144 |
| | Plastic deformation | Excessive load, surface yielding, lubricant contamination | High noise levels | Surface damages resulting in vibration, noise and eventual failure | 6 | 5 | 4 | 120 |
| | Thermal fatigue | Incorrect heat treatment, cooling system failure | Excessive heat increment during normal operation | Tooth failure | 7 | 4 | 3 | 84 |

**Table 3.12 continued from previous page**

| COMPONENT | | FAILURE MODE | CAUSES | SYMPTOMS | EFFECTS | SCORE | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | S | O | D | RPN |
| Harmonic Drive | | Tooth bending fatigue | Surface contact fatigue, gear overload or cyclic stressing of the gear tooth at the root beyond the endurance limit of the material | Adjacent teeth to the failed one showing early crack development | Tooth failure, fatigue crack initiation, complete failure of the gear | 8 | 7 | 4 | 224 |
| | | Crack on the rear cross section of Flexspline | Manufacturing defect, dynamic stress condition: deformation, rotation and meshing force | No normal meshing state, efficiency loss | Teeth and bearing wear, plastic flow, catastrophic failure in case of crack propagation to the front | 9 | 7 | 5 | 315 |
| | | Cup diaphragm failure | Transformation stress, cyclic loading, local micro-cracks, shear stress | No smooth transmission, excessive vibration | Failure in transmission of the output torque | 8 | 6 | 5 | 240 |
| | | Ratcheting phenomenon | Excessive load, improper tooth engagement (coning angle), thermal stress | Increased vibration | The FS is not concentric with the CS, FS fatigue failure, teeth wear | 8 | 3 | 3 | 72 |
| | | Lubrication defect | High temperature, contamination after wear, excessive operating speed | Excessive heat increment during normal operation | Surface scratching, friction and wear increase | 8 | 5 | 3 | 120 |
| | | Corrosive Wear | Water or additives contamination in the lubricating oil | Deterioration of the gear surface from chemical action | Acceleration of the failure faitgue | 6 | 4 | 4 | 96 |
| | | Scoring/Scuffing | Overheating, failure of the lubricant film due to contamination under excessive pressure | Rough teeth surface, long scratches in the direction of motion | Metal-to-metal contact and alternate welding and tearing of the surface metal | 7 | 4 | 4 | 112 |
| | | Gear overload | Bearing seizure, misalignment of a failed bearing, system dynamic loading, contaminants entering mesh area | Incresed noise and vibrations | Tooth failure, crack development | 7 | 5 | 3 | 105 |
| Encoders | Optical Encoders | Seal failure | Environment (contaminants, dust) | Dirt and water penetration, block of optical process | Erroneous output signal, loss of precision | 6 | 4 | 3 | 72 |
| | | Seal failure | Temperature cycling | Condensation of moist air, block of optical process | Erroneous output signal, loss of precision | 6 | 5 | 3 | 90 |
| | | Electrical failure | Temperature cycling, wiring issues (short circuits) | Intermittent current signal | Component breakdown, loss of precision, motor control loss | 8 | 4 | 2 | 64 |
| | | Mechanical break-down of internal component | Shocks and vibrations | Disk fracture, frequency variation of position signal | Total break down of component, motor control loss | 8 | 3 | 2 | 48 |

**Table 3.12 continued from previous page**

| COMPONENT | | FAILURE MODE | CAUSES | SYMPTOMS | EFFECTS | SCORE S | O | D | RPN |
|---|---|---|---|---|---|---|---|---|---|
| | | Cable broken | Vibrations, high temperature, corrosion | No feedback | No output signal, motor control loss | 7 | 3 | 2 | 42 |
| | | Misalignment of internal component | Vibrations, high load, worn bearing | Wobbling of motor shaft | Bearing damage, misalignments | 6 | 6 | 4 | 144 |
| | Magnetic | Cable broken | Vibrations, high temperature, corrosion | No feedback | No output signal, motor control loss | 7 | 3 | 3 | 63 |
| | | Interference | EMI/radiated noise | Intermittent output signal | Erroneous output signal | 4 | 6 | 4 | 96 |
| | | Mechanical damage | Excessive vibrations, shocks, jolts | Damage to integrated circuit | Failure of component | 8 | 2 | 2 | 32 |
| Bearings | | Spalling | Insufficient/excessive lubrication, distorted bearing seal, excessive load (or shock load), rapid load direction change, misalignment | Increased vibration, metal flakes separation | Increased risk of jamming, increased noise | 8 | 6 | 4 | 192 |
| | | Scoring | Natural degradation, overloads, fretting fatigue | Noise, increased friction, interferes with the normal lubricant film and increases the metal-to-metal contact | Motor loss/increased risk of jamming | 8 | 6 | 4 | 192 |
| | | Indentation | Overloads, solid contaminants in lubricant | Increased friction, increased vibrations | Increased risk of jamming, wear | 9 | 5 | 5 | 225 |
| | | Brinelling | Overloads or impact, excessive speed, static vibrations (transport, storage, idling) | Increased friction, increased vibrations | Increased risk of jamming, increased vibration, noise, friction and wear | 6 | 2 | 6 | 72 |
| | | Adhesive wear | Severe acceleration, inadequate lubrication | Localized temperature rise | High friction, high temperature | 8 | 8 | 4 | 256 |
| | | Abrasive wear | Natural degradation, insufficient/ contaminated lubrication | Noise, increased friction, temperature rise of lubricant | Performance loss, increased backlash,decrease in lubricant viscosity | 8 | 8 | 4 | 256 |
| | | Plastic deformatin | Yield strength of material exceeded, overload, indentation from debris | Change in bearing surface profile, high noise | Increased friction and wear | 8 | 6 | 5 | 240 |
| | | Pitting | Fatigue degradation, excessive lubrication, misalignment | Noise, increased friction, increased vibrations | Performance loss, grip, noise | 4 | 4 | 6 | 96 |
| | | Corrosion | Insulants degradation, lubricant chemical contaminants | Increased vibration, metal flakes separation | Increased risk of jamming, increased surface roughness | 7 | 6 | 6 | 252 |
| | | Leakage/Seal degradation | Natural degradation, harsh environment, wear, housing too tight | Excessive heat, lubricant contamination/oxidation | Lubricant bleeding and starvation, performance degradation, risk of seizure | 7 | 5 | 3 | 105 |

**Table 3.12 continued from previous page**

| COMPONENT | FAILURE MODE | CAUSES | SYMPTOMS | EFFECTS | SCORE | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | S | O | D | RPN |
| Bearings | Electric erosion (metal bearing only) | Insulants degradation, electric motor shorts, current leakage | Noise, efficiency loss, increased friction | Increased noise | 7 | 2 | 4 | 56 |
| | Tracks/Balls crack | Overloads, excessive vibration, high temperature, excessive speed, improper mounting | Noise, increased vibrations | Actuator loss (possible jamming) | 9 | 4 | 6 | 216 |
| | Scratching | Inadequate sealing, contaminants in the lubricant or installation damage | Noise, increased friction | Possible crack development and increasing friction | 7 | 6 | 4 | 168 |
| | Smearing | Unlubricated sliding contact, excessive vibrations, excessive speed, rapid change in direction of load or rotation | Excessive noise levels | Increased vibrations, increased friction, stiction | 6 | 2 | 6 | 72 |
| | Fretting | Improper fit between bearing and shaft, incorrect clearence, looseness, improper loading | Wear or score in the surface, excessive shaft movement | Allows movement of the race in relation to the shaft, damaging the surfaces and preventing a fixed contact | 7 | 2 | 6 | 84 |
| | Lubrication system failure (oil lubricated bearing only) | Fail to supply any lubricant, manufacturing defect | Excessive contact, high temperature | Bearing seizure, increased noise and vibrations | 9 | 2 | 4 | 72 |
| | Lubrication defect | Insufficient/excessive lubricant, contamination | Excessive heat, local discoloration | Increase friction forces and bearing temperature | 7 | 5 | 4 | 140 |
| | Subsurface fatigue | Cyclic stress, insufficient/excessive lubricant, excessive heat | Increasing noise and vibration levels | Possible development of cracks | 7 | 3 | 7 | 147 |
| | Surface fatigue | Loss of lubricant, corrosive agents, distorted bearing seals, inadequate heat removal | High temperature, excessive noise | Formation of pits on the surface, increase in wear and friction | 8 | 4 | 7 | 224 |

**Table 3.12:** FMECA table on components of a robotic joint

# Chapter 4

# FTA: Fault Tree Analysis

FTA (Fault Tree Analysis) method was developed in the early 1960s to analyze rocket-launch control systems from the safety point of view. This technique has rapidly gained favor because of its versatility in degree of detail when dealing with complex systems. Today, it is one of the main method used across many diverse areas to analyze various types of problems related, directly or indirectly, to reliability and safety [85]. Although FTA is a common and useful tool in many applications, often used in industry for computer control systems and large industrial plants, it has only recently been applied to robots [86, 87].

While FMECA is an inductive[1] and bottom-up method, since the analysis starts at the component level where the possible failure modes are identified and it is examined what the effects on a higher level are, FTA is a deductive[2] and top-down method that is used to map the relationships between events such as sub-system

[1]Inductive approach: reasoning from individual cases to a general conclusion. In the consideration of a certain system, it is the postulation of a particular initiating fault and the consequent attempt to ascertain the effect of that fault on system operation. [88]

[2]Deductive approach: reasoning from the general to the specific. In a deductive system analysis the starting point is the system failure from which system modes/components that have contributed to the failure are searched and analyzed. [88]

failures and their causes. A full description of the structural interactions of failure modes in the system can be derived using FTA.

## 4.1 FTA method description

A fault tree may simply be described as a logical representation of the relationship of primary fault events, called "basic events", which typically are component failures, that lead to the occurrence of a stated undesirable event, known as “top event” or "Top Level Event (TLE)", which typically is a system failure, critical from a safety standpoint. This analysis has a tree structure with logic "gates" such as OR and AND, which are used to highlight failure paths representing the flow of fault events. The gates show the relationships between circumstances needed for the occurrence of an higher event. The higher event is the output of the gate, while the lower events are the inputs to the gate [88]. Essentially, the sequence of events which could lead to a given critical system failure scenario are identified and logically combined into a tree structure. As reported in [85], some of the purposes of performing FTA are as follows:

- understanding the level of protection that the design concept provides against failures;
- understanding the functional relationship of system failures, which was not possible through FMECA;
- identifying critical areas and potential developments for cost-effective improvements.

**Top-down development of the Fault Tree**

To develop a fault tree, the following basic steps are generally required: it begins by identifying an undesirable event, called the "top event", associated with a system under consideration. The top event is broken down into intermediate events that can, through some logical combination, cause the failure at the top. The construction of the fault tree proceeds by generating fault events in a successive manner until the fault events do not need to be developed any further. These fault events are known as basic events, they are input fault events which can be considered identifiable and independent faults. At this stage the FMECA analysis plays an important role in isolating these basic events. Some conditions or causes may be left undeveloped if the probability that they will occur is small enough to be ignored [89]. During the process of fault tree construction, it is successively asked the question: "How could this fault event occur?" [85].

Fault tree analysis is usually carried out in five steps:

1. definition of the problem, system, and boundary conditions of the analysis;
2. construction of the fault tree;
3. identification of minimal cut sets;
4. qualitative[3] analysis of the fault tree;
5. quantitative[4] analysis of the fault tree.

[3]Qualitative: data can be categorized based on traits and characteristics.

[4]Quantitative: data can be counted, measured, and expressed using numbers.

A cut set in a fault tree is a set of basic events whose (simultaneous) occurrence ensures that the Top Event occurs. A minimal cut set is a cut set that cannot be reduced without losing its status as a cut set. The Top Event occurs if one or more of the minimal cut sets occur.

## 4.2 Building Blocks of the Fault Tree Analysis

A typical fault tree is composed by a number of symbols which are described in detail in the following section. Basic symbols used while constructing fault trees are shown in Figure 4.1.

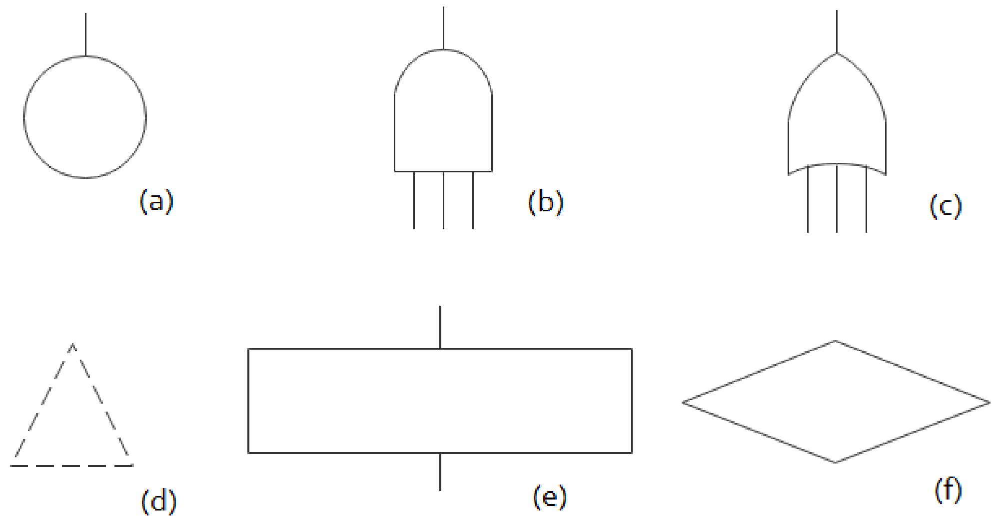


**Figure 4.1:** Fault tree analysis symbols: (a) circle, (b) AND gate, (c) OR gate, (d) triangle, (e) rectangle, (f) diamond. [85]

All the six symbols shown in Figure 4.1 are described below. Their definitions are taken from [85, 88].

- **Circle**: it denotes a basic or primary fault event (e.g., failure of an elementary part or component). The circle describes an initiating fault that requires no further development since appropriate resolution has been reached. To these events may be assigned quantitative parameters in order to evaluate the reliability of the entire system. The parameters of the event are: probability of occurrence, failure rate and repair rate whose values are normally obtained from empirical data.

- **AND gate**: it represents an output event that occurs if and only if all of the input fault events occur.

- **OR gate**: it represents an output fault event that occurs if one or more of the input fault events occur.

- **Triangle**: it indicates a suppressed tree, which is developed in another sub-tree.

- **Rectangle**: it is used to indicate the "top event" or an "intermediate event": it denotes a fault event that occurs from the logical combination of fault events through the input of a logic gate such as AND and OR.

- **Diamond**: it represents a fault event for which the causes are left undeveloped.

There are other gate symbols, which are not used in this thesis project since they do not reflect the relationship among the analyzed components. These gates are:

- **Exclusive OR**: the output event occurs if exactly one input occurs;

- **Priority AND**: the output occurs if the inputs occur in a specific sequence specified by a conditioning event;

- **Inhibit gate**: the output occurs if the input occurs under an enabling condition specified by a conditioning event.

## 4.3 FTA Advantages and Disadvantages

Like any other technique, there are many advantages and disadvantages of performing FTA. Some of its advantages, as reported in [85, 90], are as follows:

1. allows concentration on one specific failure (top event) at a time;
2. offers a graphic tool for management;
3. highlights the critical elements of the system related to reliability. The FTA process may lead to a single component that causes many paths to failure, thus improving that one element may minimize the possibility of other failures;
4. expose system behavior and possible faults interactions. FTA allows the examination of the several ways a fault may occur and may find non-obvious paths to failure considering interconnections of components;
5. useful to handle complex systems more easily;
6. requires the analyst to understand thoroughly the system under consideration before starting the analysis;
7. useful to provide options for management and others to perform either qualitative or quantitative analysis;
8. useful to highlight failures deductively and to provide insight into the system behavior.

In contrast, some of the disadvantages, again according to [85, 90], of the FTA are:

1. time-consuming and costly method;
2. the end results are difficult to check;

3. it considers parts or components in either working or failed state (i.e., the partial failure states of the parts or components are difficult to handle, degradation of performance is not considered);

4. to include all types of common-cause failures it requires a considerable effort.

A common-cause failure is defined as "any instance where multiple units or components fail due to a single cause" [90]. Some of the common-cause failures may occur due to:

1. **Equipment design deficiency**: includes those failures that may be due to interdependence between electrical and mechanical subsystems or components.

2. **External environment**: this includes causes such as dust, dirt, humidity, temperature, moisture and vibration. Features that are related to the operating environment.

3. **Common manufacturer**: redundant equipment from the same manufacturer may have the same fabrication errors/defects.

4. **Common external power source**: a common-cause failure may occur due to a failure at a common external power source between components.

## 4.4 FTA on robot joint

It is important to understand that a fault tree is not a model of all possible system failures, but it is tailored to its top event, so it is a specific analysis of a particular system failure mode, and thus includes only those faults that contribute to the examined top event. It must be pointed out that a fault tree is not in itself a quantitative model. It is a qualitative model that can be evaluated quantitatively. The fact that a fault tree is a particularly convenient model to quantify, does not change the qualitative nature of the analysis itself [88]. The purely qualitative FTA can be extended into a quantitative FTA by adding quantitative information of component reliability (e.g., failure rates). The basic mathematical technique involved in the quantitative assessment of a fault tree is the probability theory. Probability theory provides an analytical treatment of events, and events are the fundamental components of fault trees. Moreover, a fault tree can be thought of as a pictorial representation of Boolean relationships among fault events that cause the top event to occur. In fact, a fault tree can always be translated into an entirely equivalent set of Boolean equations [88]. The two basic gate categories used in the FTA analysis performed on the following pages are the OR-gate and the AND-gate. Because these gates relate events in exactly the same way as the Boolean operations do, there is a one-to-one correspondence between the Boolean algebraic representation and the fault tree representation.

- The OR-gate is equivalent to the Boolean symbol "+". For example, the OR-gate with two input events, $A$ and $B$, is equivalent to the Boolean expression, $Q = A + B$. Either of the events $A$ or $B$, or both must occur in order for $Q$ to occur.

- The AND-gate is equivalent to the Boolean symbol"·". All of the input events attached to the AND-gate must occur in order for the event above the gate to occur. For two events, $A$ and $B$, attached to the AND-gate, the equivalent Boolean expression is $Q = A \cdot B$, where $Q$ is the output event.

Then the probability of occurrence of those events must be evaluated accordingly, for example: in the OR-gate case, if $A$ and $B$ are mutually exclusive events, then $P(A \cup B) = 0$, and $P(Q) = P(A) + P(B)$.In this way, recalling probability theory and Boolean algebra, it is possible to assign a probability of occurrence to each intermediate event, up to the Top Level Event.

The fault tree analysis presented in this study is an entirely qualitative model due to lack of available reliability data for robots and their subsystems. In fact, as already pointed out in the course of this work, the main problem encountered in performing this type of analysis on robotic manipulators was the lack of quantitative data found in the literature. However, the purpose of this research is to demonstrate fault tree analysis as a tool. In addition, most of the fault tree analyses in robotics have focused on qualitative, rather than quantitative, analysis. Robotic manipulators present some peculiar problems, due to the complex and strongly coupled nature of their sub-systems [87].
Robotic systems are actually very complex to analyze using FTA: several faults may also be interconnected creating lateral branches or cycles in the fault tree. In some robots, one motion at a joint may be coupled with the motion of another joint such that failure to either one of them causes the failure of the other. It is also difficult to determine the relationships between some failures. For example, the failure of all the internal feedback sensors at the elbow joint of a robot may make the robot controller blind to the elbow position. The elbow has not actually failed, but the robot is unable to detect the results of any commands sent to the elbow. Thus, the sensor malfunction does not contribute to an elbow failure specifically, but may cause a failure of the entire robot. Relationships like this one make the

tree complex and difficult to understand [89]. Another critical complication with robot manipulators, that is useful to better understand the coupled nature of faults, is that faults in those subsystems in motion within the arm (sensors, actuators) will be configuration-dependent, i.e. vary with each manipulator motion trajectory. This means that coverage models must be augmented with trajectory dependent information. For example, consider joint position sensor fault. For the manipulator performing a “pick and place” task, it is mostly the shoulder and elbow joints that are used for the greatest part of positioning. In this case, the wrist joints are moved very sparingly, if at all. Thus, the wrist sensor readings are largely isolated from sensor readings concerning the rest of the arm, and spurious or wrong wrist sensor readings, due to a terminal sensor fault, will be relatively easy to distinguish and isolate. However, in the case of rapid fine motions, largely involving the wrist joints, dynamic coupling between the wrist joints can introduce significant errors in the controller, which enter the erroneous sensor readings as extra noise [87].

### 4.4.1 FTA performed on UR5

In the development of the FTA, the analysis was divided into four levels.

1. **Plant shutdown**.

   At the highest level the "Top Event" can be found, which was considered to be the plant shutdown (Fig. 4.2). This undesirable event can be caused by either one of the "intermediate events" taken into consideration, which are connected through an OR gate:

   - **robot failure** (which is further developed in this analysis);
   - **tool failure** (end-effector failure, left undeveloped);
   - **power failure** (not developed);
   - **external sensor failure**: for what concerns external sensors, a further

level of analysis was developed for identifying possible causes of failure distinguishing between: torque/force sensor failure, optical sensors failure, IMU (Inertial Measurement Sensors) failure (e.g. accelerometers, gyroscopes, magnetometers) and collision detection failure;

- **external factors**.

The tool analysis was left undeveloped as it is too circumstantial in nature. In fact, a robot can be used for a variety of operations and therefore it would use different tools. Consequently it would have been impossible to analyze every failure related to each single tool. Furthermore, there can be simple tools, which have no moving parts or electrical components, such as a screwdriver, which will never fail unless it breaks. But there are other cases in which there are much more complex tools, such as grippers or combinations of tools: e.g. camera + force sensor + gripper. Therefore this branch was left undeveloped because a specific analysis should be made for the single tool installed and it would not be possible, or not convenient, to make an analysis on all the possible tools of a robot.

Power failure analysis is also left undeveloped since in this work the main focus was on the robotic arm and furthermore the power failure can also involve other failures in the manufacturing plant, therefore not specific to the robot.

External sensors failure was considered at this level since a failure at this type of equipment will not lead to a robot failure but rather it will lead to a plant shutdown, since the robot may no longer be able to perform its task correctly, but it has not failed. In order to avoid losses in the production, after an external sensor failure, processing may be stopped in order to perform repairments, replacements or recalibrations of sensors.

2. **Robot failure**.

   At the first intermediate level, the robot failure is analyzed, which is the main purpose of this research (Fig. 4.2). More detailed analysis focuses on the joints which build up the robotic arm, but here a general view of the system is provided. For completeness of analysis, link failure has also been added at this level, even though for the case study of this research (i.e. UR5), it is not considered a possible failure cause, as already explained in Sec. 2.4. Several failure causes are identified, all connected through an OR gate, as it is enough for a single failure event to happen for the robot failure to occur:

   - **joints failure**: all six joints are connected in parallel to another OR gate, since the failure of a single joint will cause the entire robot to stop functioning;
   - **power failure** (not developed);
   - **control unit failure**: this was not the intent of this thesis, but it was still mentioned because software errors can also lead to failures;
   - **link failure**;
   - **external factors**: such as human errors or accidental damage.

   For what concerns the link failure, a deeper investigation was performed, listing the possible failure causes for this component which are: transmission organ failure, mechanical breakage, communication wiring issue and power wiring issue. In this particular study case these failures are left undeveloped since in the UR5 every single joint includes a complete embedded actuation system, so it was not necessary to insert motion transmission mechanisms in between joints. UR5 links are just rigid organs that contains power wiring connected to sensors and motors. On the other hand, considering larger industrial robots, which, in order to have a lighter and more compact wrist and to avoid large inertia at the end of the robotic arm, mounts the three wrist motors near the elbow joint, a deeper analysis concerning transmission systems (which can be shafts or toothed wheels with transmission belts) should be developed.

3. **Joint failure**.

   At the next intermediate level the joint failure was considered. At this stage the FMECA analysis, previously performed in Sec. 3, has played a fundamental role in identifying the components that make up the joint and their possible causes of failure. Joint failure output event is obtained through the combination of several input fault events connected with an OR gate, as shown in Fig. 4.3. Robots are closed-loop controlled systems and there are three control loops on each joint, one for current, one for speed and one controlling position. This means that if even a single joint sees an error greater than a threshold specified by the manufacturer, in this case Universal Robots, the robot automatically undergoes an emergency stop. For this reason, a single joint failure is enough to stop the whole robotic system and therefore this is the reason why OR gates are used. As highlighted through the FMECA, the possible causes for robot joint failures are directly connected to the components of the joint:

   - **motor failure**;
   - **gearbox failure**;
   - **encoder failure**;
   - **bearings failure**.

4. **Component failure**.

   As last level of analysis, at the bottom of the tree, the single basic joint components are investigated (FTA are shown from Fig. 4.4 to Fig. 4.8). Also at this stage the previously performed analysis through the FMECA was of major help, allowing to detect the basic events. In the following FTA analysis the basic events failure causes are not developed, but for a deeper understanding of the degradation phenomenon that leads to the occurrence of the failure event, reference is made to the Section 3, where it was deeply analysed.

In the following pages the tree diagrams representing FTA are shown. In Fig. 4.2 the top level FTA is performed, followed by the intermediate robot failure event and joint failure, shown in Fig. 4.3 and, with regard to the remaining figures, electric motor (Fig. 4.4), harmonic drive (Fig. 4.5), magnetic encoder (Fig. 4.6) and bearings (Fig. 4.8) failure are analyzed. Notice that also optical encoder FTA was performed, and it is shown in Fig. 4.7.

The following papers/articles/researches [86, 91–97] were used as guidelines, together with the FMECA analysis previously performed.

Note that in the top layers it was added a not developed failure event, indicated as "external factors". By this expression are denoted all those errors, accidents, unforeseen events, human errors, programming errors and other external factors which are not predictable by their nature and therefore cannot be described, as they can lead to very different effects on the system. Therefore they have been placed at a high level in the FTA.

It is also important to underline that "wear" is a complex factor to consider inside an FTA, since although it is not considered to be a failure on its own, it surely leads to a failure, depending on its severity. For example, in Fig. 4.5, when dealing with "tooth wear" in the Harmonic Drive, this phenomenon certainly reduces the component transmission performances, but the reducer system is still operational. However, since there are control loops inside the joint, if the detected transmission is not the nominal one and its value falls below a certain threshold (an event that can very well be caused by wear), there is a robot failure, leading to an emergency stop. A similar reasoning may be applied to bearings in Fig. 4.8.

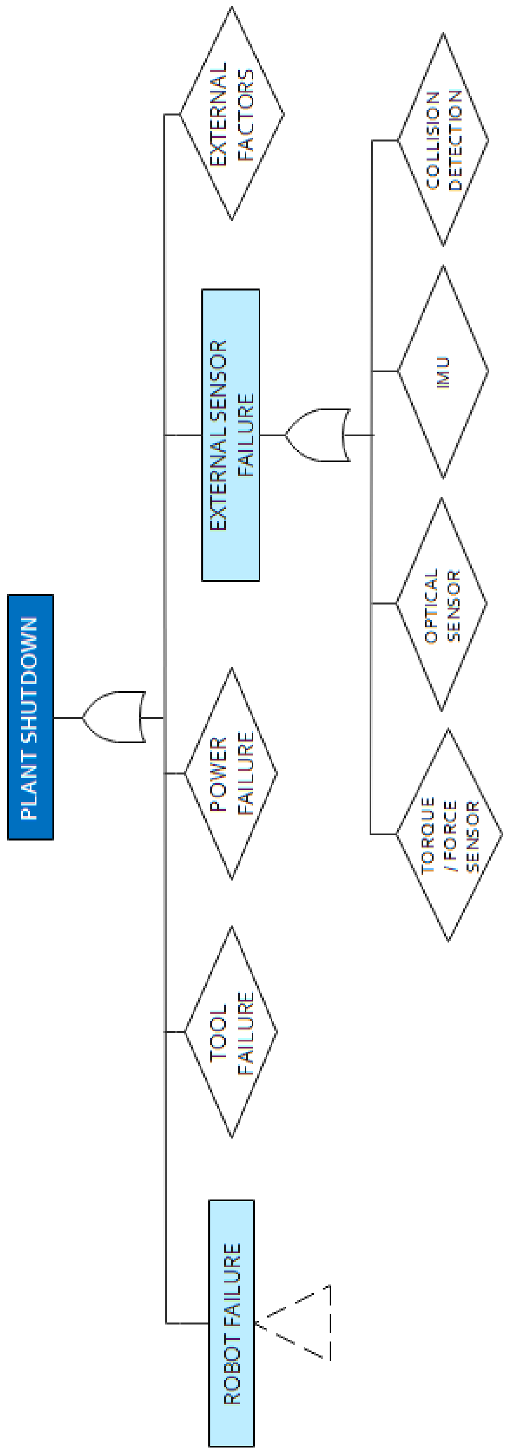


**Figure 4.2:** Top level event FTA

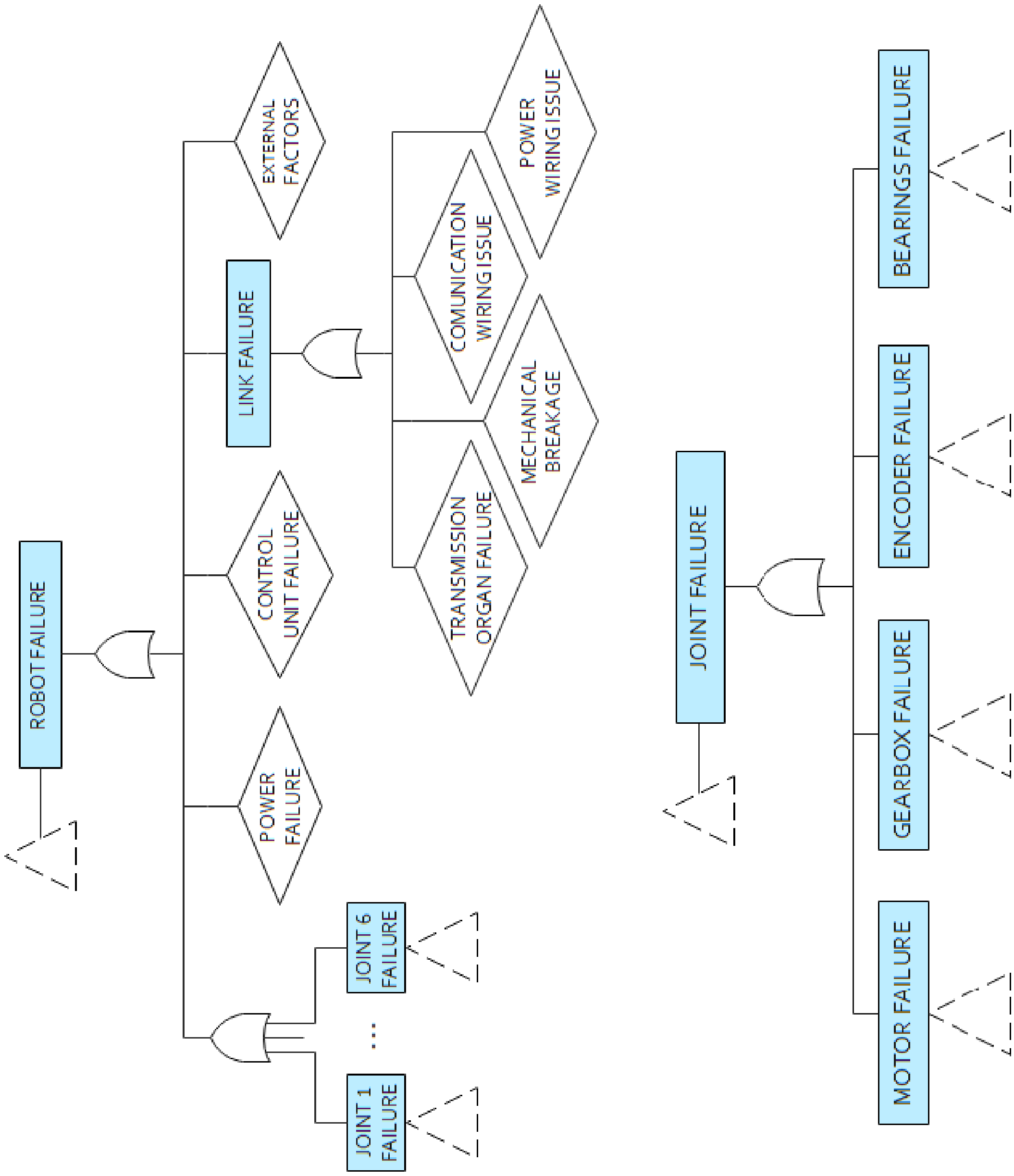


**Figure 4.3:** Robot failure and Joint failure FTA

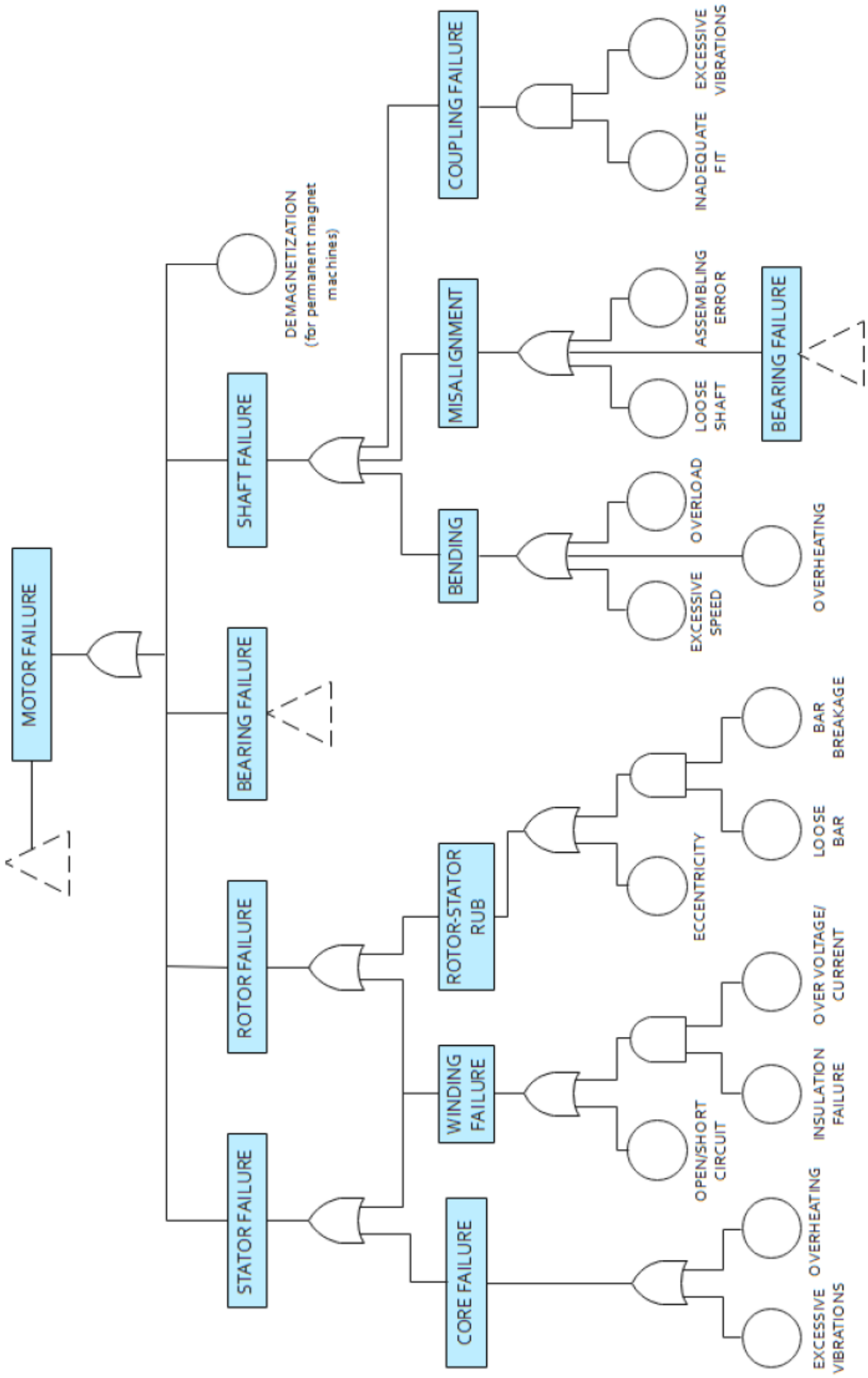


**Figure 4.4:** Electric Motor failure FTA

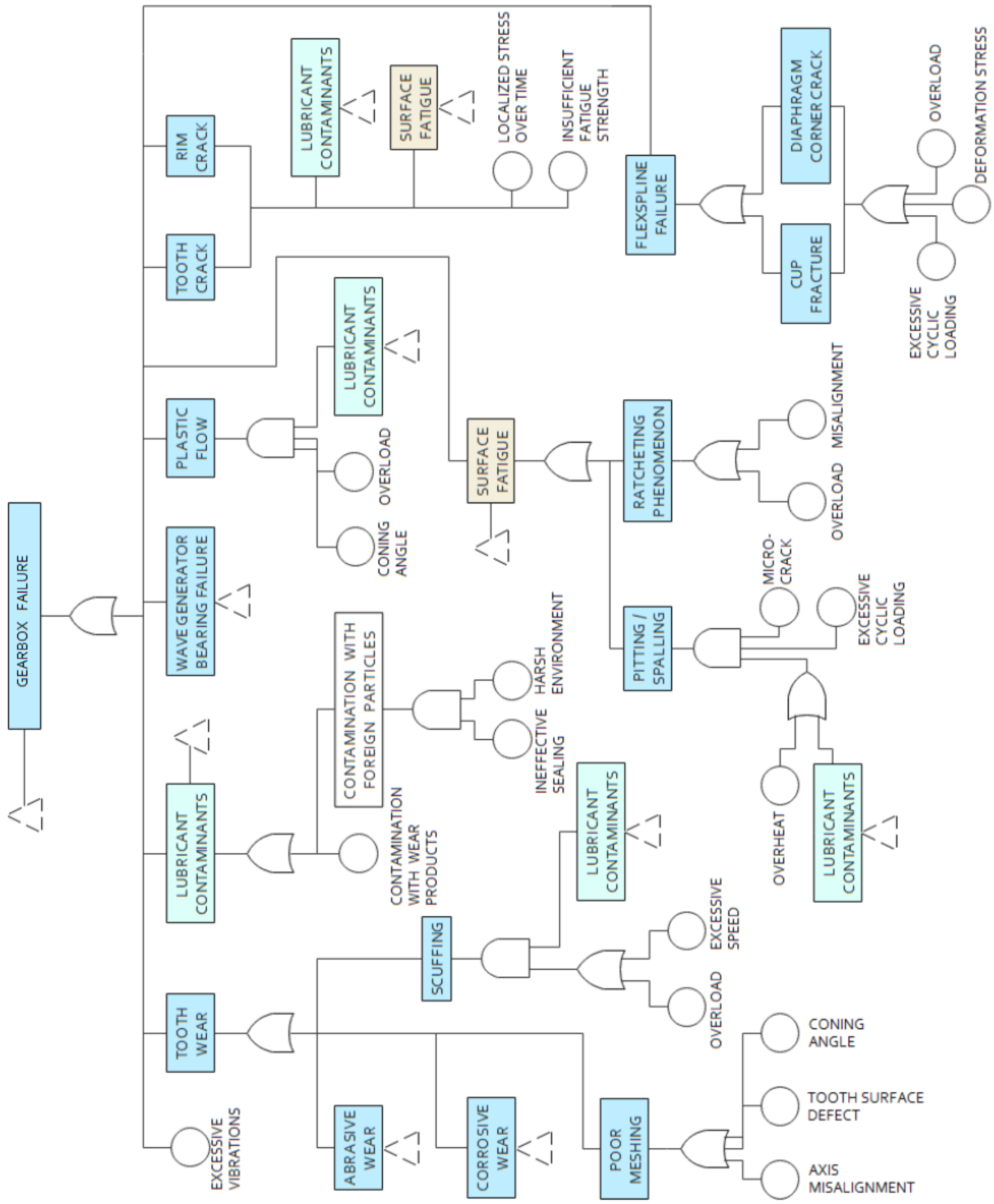


**Figure 4.5:** Harmonic Drive failure FTA

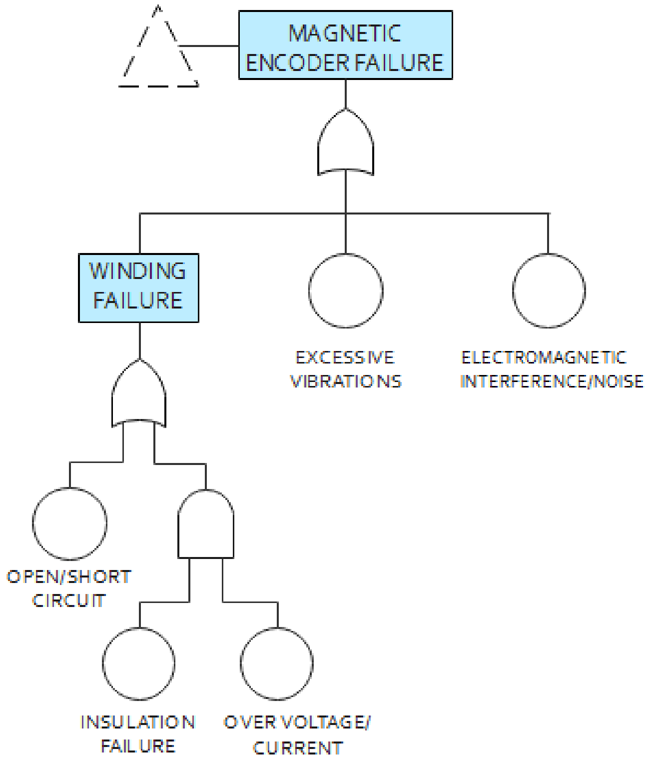


**Figure 4.6:** Magnetic rotary absolute encoder failure FTA

For completeness of the analysis, here is reported the FTA for optical encoders, which are not the components mounted on the UR5 taken as case study, since a FMECA analysis was also performed for this type of component, thus it can be useful for other industrial robots.

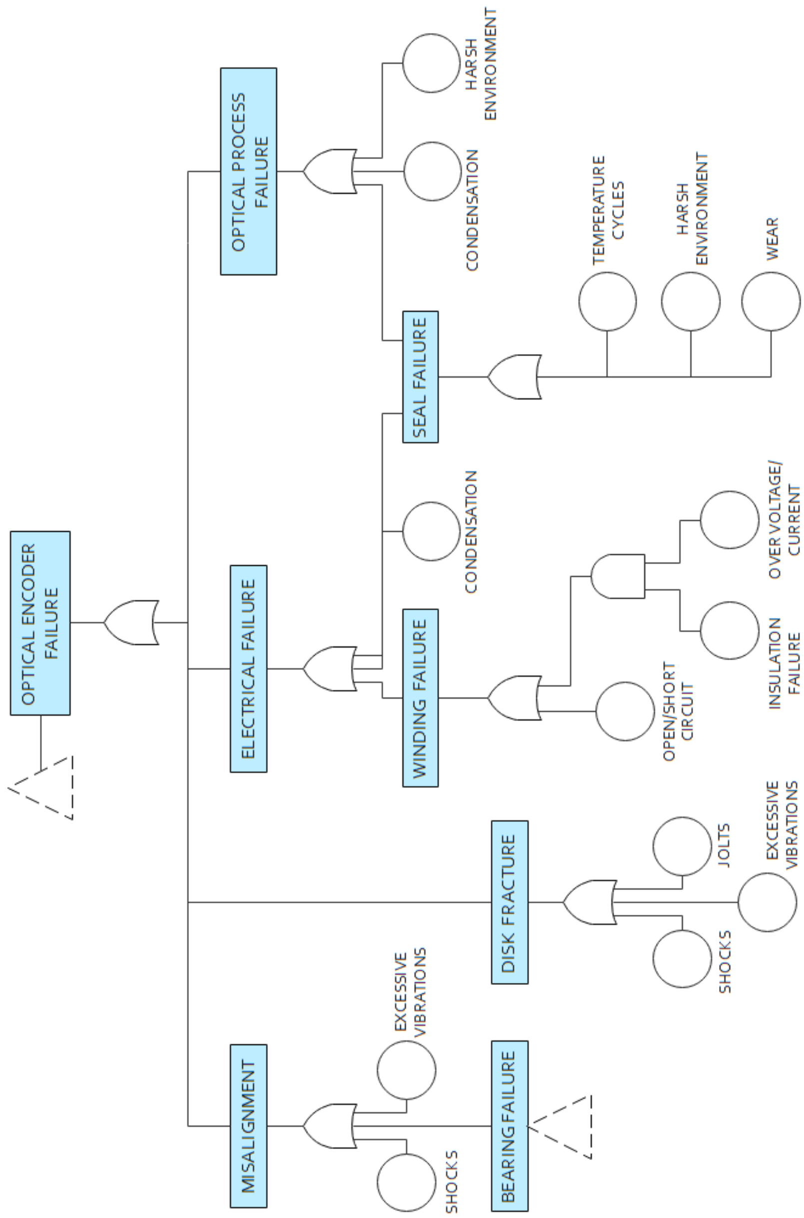


**Figure 4.7:** Optical absolute encoder failure FTA

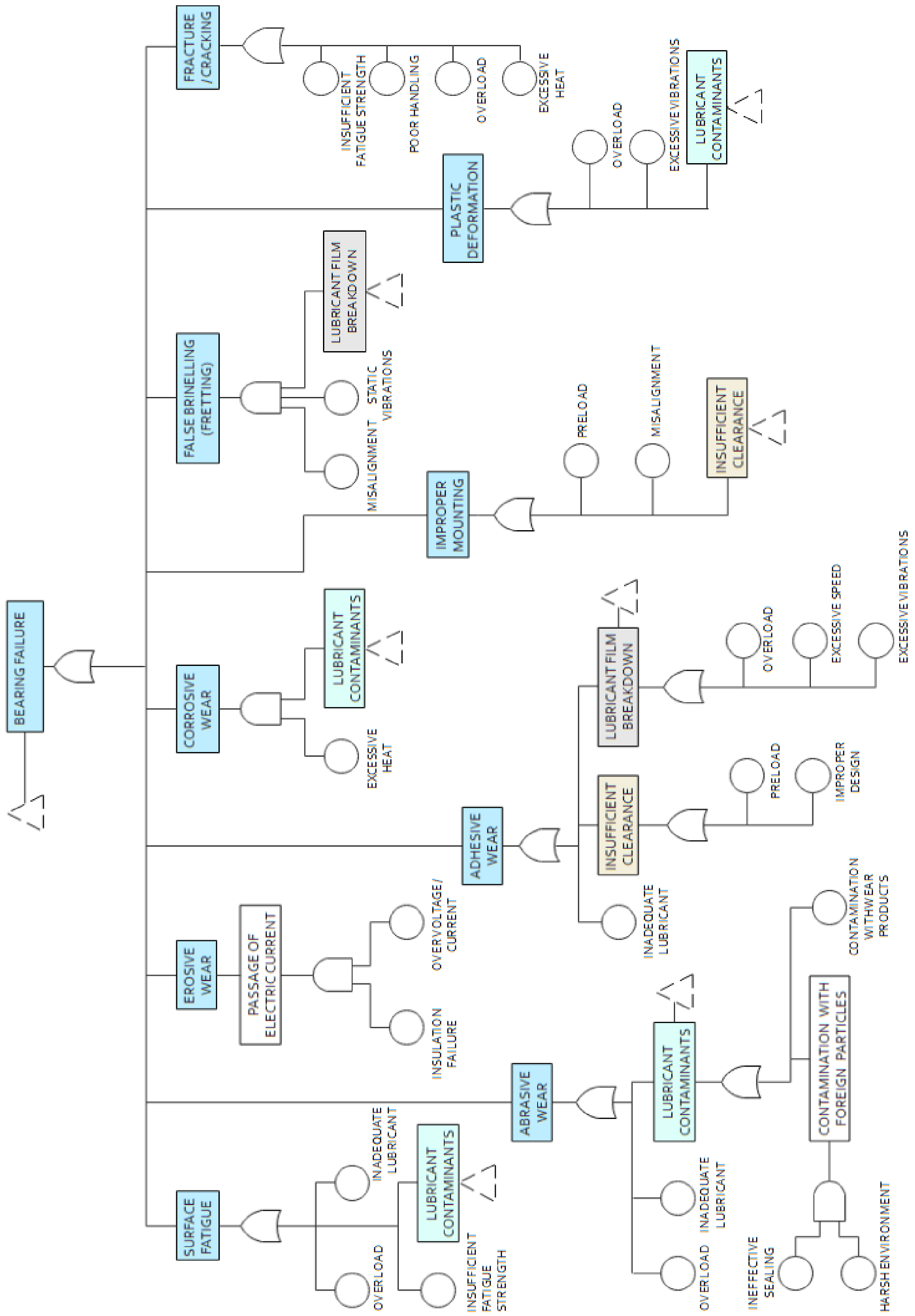


**Figure 4.8:** Bearing failure FTA

### 4.4.2 Further developments for FTA in robotics

Once the fault tree is built, the information available may be enhanced by a quantitative analysis of the failures. Failure rates are assigned to each input event and propagated up the tree based on the rules of the connecting logic gates. The output of an OR gate is the sum of the inputs. The resulting probability of the combined input events is greater than the probability of an individual input event. The output of an AND gate is the product of the inputs. The resulting probability of all the events occurring is thus less than the probability of any one occurring. The AND gates represent some form of redundant measurement or capability and are more desirable in the fault tree as the probability of a failure decreases through the combination of lower level events.

For what concerns the FTA just performed, it must be reminded that the analysis is limited to a qualitative approach due to lack of quantitative data regarding reliability and failure probability of components, but having completed the tree structure it will be easy to perform a quantitative analysis, following the logic explained in Sec. 4.4. So if in the future these data were to be found, the integration in this type of analysis would be immediate.

# Chapter 5

# Conclusions and Further Developments

It is becoming clear that with the increasing application complexity facing robotics, with reports of robots planned for use in surgery, domestic and other critical applications, human safety must be ensured as a priority. For what concerns industry, as robotic technologies are becoming increasingly important within complex manufacturing environments, improving productivity, availability and safety, robot system reliability has become more critical, since the fault of individual robot components can cause the stoppage of the entire production system. Unexpected downtime and lost production translate into financial losses for manufacturers, which consequently are increasingly interested in preserving the health of their robots, through Condition Base Maintenance (CBM) techniques, resulting in long term cost savings. Condition monitoring and health prediction for industrial robot systems, which are high capital goods, can enhance mechanical reliability and reduce overall maintenance costs.

This research aimed to verify the efficiency of the PHM methodology through the availment of diagnostics and prognostics tools applied to a robotic joint of the UR5, starting from the detection and identification of faults and failures, ranking the most critical components in the system through the FMECA analysis, and moving on the research development studying the relationships between the most common faults using a FTA analysis. FMECA was propeduetic to FTA in the sense that it provided the "basic faults" on which the interdependence was then analyzed in detail, highlighting the influence of multiple components in the system.

**FMECA results**

A deep study of the individual components failure mode was initially performed, and Table 3.12, which considers failure causes, symptoms and effects, was developed, for ultimately investigate on the most critical components, evaluated through the RPN index. The main results obtained through the FMECA analysis are the following:

- it is possible to state that the most critical component of the robotic joint system is the **electric motor**. Being the motor the power system of industrial robots and the "muscle" of robot movements, it is not surprising to find that the motor is the component with highest average RPN among all, with a value of: $RPN_{AVG} \approx 211.9$.
  The other values for the average RPN are:
  - Harmonic Drive: $RPN_{AVG} = 152$;
  - Encoders: $RPN_{AVG} \approx 72.3$;
    considering Optical Encoders the average RPN is $\approx 76.6$,
    while for Magnetic Encoders the average RPN is $\approx 63.6$;
  - Bearings: $RPN_{AVG} \approx 163.7$.

- As expected, the most robust component among the analyzed ones is the magnetic encoder, also due to the fact that its failure modes are few and require very critical conditions, which means that most likely the failure of another component would arise sooner with respect to the encoder failure.

- It is important to underline that the components with the highest average severity value are the **bearings**, with an average severity rate of: $S_{AVG} \approx 7.4$. Through the FMECA analysis it was possible to ascertain how for all joint components the bearings constitute a critical point of the system, and this criticality will then be better investigated through the FTA. Concerning the average severity values for failure modes of the other components of the joint:
  - Electric Motor: $S_{AVG} \approx 7.1$
  - Harmonic Drive: $S_{AVG} \approx 7$
  - Encoders: $S_{AVG} \approx 6.7$;
    considering Optical Encoders the average S is $\approx 6.8$,
    while for Magnetic Encoders the average S is $\approx 6.3$.

These information are of great help for the physic-based model prognostic approach, indicating where to pay more attention in the model development, what types of simulated faults have to be inserted into the high fidelity model of the UR5 collaborative robot in order to have data on possible non-nominal behavior of a robot due to faults that have a greater probability of occurrence, or that are more critical for the system.

**FTA results**

FTA was developed to tackle the reliability analysis from the entire system point of view and to understand the logic of cause/effect leading to the "top event". The main results obtained from the FTA are listed below:

- it is clear that **bearing failure** is the most critical one, when considering the whole system. This is evident since bearings are the only component to appear as a subtree in each FTA of every single other component. As a matter of fact bearings are essential for the correct functioning of the other components of the joint.

- The most common "basic event" was found to be "**excessive vibrations**", meaning that vibration analysis is certainly the strategy to follow for PHM purposes in future researches.

- Minimal cut set includes just one single basic event.

**General results**

The effectiveness of FMECA and FTA methods in evaluating aspects concerning the safety and reliability of the robotic system was therefore demonstrated and the following considerations can be made:

- FMECA is most effective when it is used by a team composed of experts in different sectors and when the team members have experience with the operation of the machine;

- due to the structured and deductive reasoning implied in FTA, it relies less on practical experience of the expert than FMECA does so it represents a good starting point in studying a system;

- FTA alone results useful for diagnostics purposes, allowing to highlight a logical sequence of events leading to failure, but it is less effective at the prognostics level, being unable to distinguish the state of degradation of the component (which is considered either working or not working);
- a common downside between the two procedures is that it takes a long time to carry out an accurate analysis.

Starting from the studies carried out in this thesis, the author suggests a targeted use of these methods, implementing a mixed analysis: FTA and FMECA can be combined in a recursive manner in a failure analysis to gain the individual benefits of both approaches. Indeed, performing separately FMECA and FTA may cause a loss of focus on the most critical parts of the system, which the failure analysis typically aims to identify. Few studies have been done in this direction, such as that of [98], where the key idea is to perform an FTA to identify failure modes and then an FMECA to assess the criticality of each failure mode top-down at three different levels: system, function and component level.
At each level the analysis can be split into two different stages:
(1) identification of failure modes;
(2) assessment of criticality.
The advantage is to only perform FTA for those functions and components that have high criticality.

A further step would be to implement a quantitative FTA by collecting data regarding the reliability of each individual component, in order to apply FTA as a numerical assessment in addition to identification of critical failure interactions, and consequently increase the safety measures that can affect the tree branches considered most critical. Preventative design measures can be taken by using high quality components, improving the environmental conditions of electronic components, and addition monitoring electronics, or redundancy to reduce the

likely occurrence of erratic robot movement in any mode of operation.
For what FMECA is concerned, given the limits related to the use of RPN, Weighted RPN (WRPN) calculation methods can be used to improve reliability of the analysis [99].

In conclusion, it was demonstrated that FMECA and FTA are excellent techniques for analyzing reliability, safety and fault tolerance in a multidisciplinary area such as robotics. Qualitative analyses have proved valuable for various robotic applications.
Although many achievements have been made in the PHM field, further research is needed in the field of robotics. The most critical problem, in general, is the little historical data availability for robotic equipment, and data collection is a major challenge. Quantitative analyses for robotics are more problematic due to this lack of data on these custom systems, therefore research should move in this direction. Regarding the author's opinion, data sharing from industrial robots of the same type, based on cloud framework, can enrich data sets and help to build more accurate models so that both the manufacturer and the end user can benefit from them.

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