Development of a new crimp-quality-monitoring system for manually operated tools

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Development of a New Crimp-Quality-Monitoring System for Manually Operated Tools

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Abstract

Development of a New Crimp-Quality-Monitoring System for Manually Operated Tools

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This thesis is concerned with the development of a novel technical solution that is aimed to improve the quality of cable crimp terminations in the electronics industry. The automotive, aero and military vehicle industries are of special interest due to their stringent requirements for guaranteed quality assurances in relation to their safety-critical products. The emphasis is on handheld crimping tools, where a new scheme for measuring the relevant crimp force is proposed using a small embedded computer to process information; so as to make an on-instrument statement regarding the crimp process quality.

The thesis includes a detailed review of the current technical practices in the cable termination business, with a particular emphasis on the quality estimations for crimped connections using the crimp force monitoring (CFM) scheme. A comprehensive study of the state-of-the-art crimp force monitoring schemes and technologies is presented.

A gap in the tool chain is identified whereby the industry has a preference for the use of hand tools in some selected processes; but the CFM scheme cannot be currently integrated directly with such hand tools. The bulk of the work in this thesis is thus focused on the development of a technical solution that will address this need for integration of hand tools with the CFM scheme. The concept is to develop a fully embedded subsystem that can be attached directly to a hand tool and this system will perform all of the signal processing and the statistical analysis so that each crimped joint can be trusted to meet the relevant stated quality parameters.

In the course of development work a fully functional prototype subsystem is developed for the CFM solution, for application to hand tools. Analytical and statistical measurement and assessment algorithms were developed to a standard, which allows a final quality rating to be applied to crimped joint connections. Such algorithms are designed to be embedded directly onto the instrument’s microcomputer.

The new system has been evaluated and tested in the course of this research project and it has currently been accepted by a number of industries for a planned volume qualification assessment.

Declaration

This thesis is presented in fulfilment of the requirements for the Degree of Masters of Engineering.

All the work detailed in this report is completely my own and has not been submitted to any other academic authority in any university. Where use has been made of the work of other people, or where any information included was taken from other sources, all such instances have been fully acknowledged and referenced.

Signature: ________________________________

Tobias Schmid

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Glossary of Terms

A

ABS	Antilock Braking System
ADC	Analog-to-Digital-Converter
AOI	Area Of Interest

B

BMW	Bayerische Motoren Werke

C

CBT	Closed Barrel Terminal
CFA	Crimp Force Analysis
CFM	Crimp Force Monitoring
CQM	Crimp Quality Monitoring

D

DAC	Digital-to-Analog-Converter

E

EEPROM	Electrically Erasable Programmable Read-Only Memory
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
ESP	Electronic Stability Control

F

FAT	File-Allocation Table
FIFO	First-In-First-Out

G

GPS	Global Positioning System
GUI	Graphical User Interface

GUM	Guide to the expression of Uncertainty in Measurement

I

IEC	International Electrotechnical Commission
I^2C	Inter-Integrated Circuit

J

JCGM	Joint Committee for Guides in Metrology

L

LPC	Loose-Piece Terminal

M

µC	Microcontroller

O

OBT	Open Barrel Terminal
OEM	Original Equipment Manufacturer
OLED	Organic Light-Emitting Diode
OS	Operating System

P

PC	Personal Computer
PCB	Printed Circuit Board

Q

QA	Quality Assurance

R

RAM	Random Access Memory
ROM	Read-Only Memory
RTOS	Real-Time Operting System
RWZ	Rennsteig Werkzeuge GmbH

S

SAE	Society of Automotive Engineers
SDI	Serial Data Input
SMD	Surface Mount Device

SPC	Statistic Process Control
SPI	Serial Peripheral Interface

T

TE	Transient Emission

U

USB	Universal Serial Bus

V

Via	is a small device to interconnect certain layers of a printed circuit board.

X

X-ray	is a form of radioactice radiation to screen an objectives inside.

Z

ZigBee	is an industrial radio transmission standard.

1 Introduction

1.1 General

This work is concerned with the development of a novel technical solution that is aimed to improve the quality of cable terminations in the electronics industry. The automotive, aero and military vehicle industries are of special interest due to their stringent requirements for guaranteed quality assurances in relation to their safety-critical products. The emphasis is on handheld crimping tools, where a new scheme for measuring the relevant crimp force is proposed using a small ‘on-instrument’ embedded computer to process information; so as to make an immediate statement regarding the crimp process quality.

A gap in the tool chain for the wire harness production industry has been identified whereby the industry has a preference for the use of hand tools in some selected processes; but the computerised quality measurement schemes cannot be currently integrated directly with such hand tools. The bulk of the work in this thesis is thus focused on the development of a technical solution that will address this need for integration of hand tools with the computerised quality scheme. The concept is to develop a fully embedded subsystem that can be attached directly to a hand tool and this system will perform all of the signal processing and the statistical analysis so that each crimped joint can be trusted to meet the relevant stated quality parameters.

Over the years the amount of electronic equipment in automotive vehicles has grown rapidly. Nowadays, almost 25% of the manufacturing costs of a car are attributed to the sum of its electronic equipment [1]. Driver assistance systems such as Anti-lock Brake System (ABS), Electronic Stability Program (ESP), Adaptive Cruise Control, GPS Navigation Systems or Parking Assistants, including cameras for a virtual surround view, are just a few examples.

In line with the growth associated technological advances there is a resulting high demand for cable connections and networking wires to allow controlled interactions between the various components. Today, a middle-class automobile comprises circa 3.5 kilometres of cables with approximately 3,000 individual connections. By comparison to the civil aviation, an aircraft such as a current ‘Jumbo-Jet’ comprises more than 500 kilometres of signal-bearing wires. Even though the automotive vehicle now has complex wiring structures, it can be assumed that there are much higher complexities and demands in the aircraft industry in relation to the on-board wiring for electrical signalling applications.

However, to guarantee a high level of mechanical and electrical reliability, all wires and the related connections need to comply with strict quality requirements for production.

Due to the realities of current manufacturing process capabilities, cable crimping continues to be the preferred method for producing the various cable connections. This type of connections has advantages, such as good vibration resistance. Crimping has won out over the alternative approach of soldering the connections. As a side effect, there is a weight saving benefit in not using soldered connections, and this impacts positively on fuel consumption and the protection of the environment.

As always, quality goals are paramount in the transport industries, and to keep this quality-awareness in mind various quality assurance (QA) methods need to be agreed in the manufacture of each single component of a wire harness.

In traditional industry practice, the majority of such QA checks for crimped components are carried out on a random sampling basis, in an off-line assessment scheme. However, in recent times a quality-monitoring tool approach is being introduced for doing the in-line QA assessment during the actual production process. Based on the crimp force monitoring (CFM) scheme the big automotive manufacturers, such as BMW, Volkswagen and Mercedes Benz, are able to significantly improve the quality level of their wire harnesses; even though the amount of electronic equipment, and therefore the number of individual connections, continues to increase every year. The continuous growth in the number of electronic components in automobiles has persuaded the manufacturers, since 1990s, to reduce the number of soldered connections in favour of the crimped wire connections. All this has led to the requirement for more control of the quality of crimp force procedures during the production process [2].

Crimp force monitoring (CFM) is a standardised, proven and trustworthy instrumented process for detecting crimping errors, or worn-out dies on crimping presses, and it is used either as a standalone facility, or it can be attached to semi-automated or fully-automated machines. However, in current practice, there is still a high percentage of wire-terminations being crimped by hand, with manual hand tools that do not support any Crimp Quality Monitoring (CQM) system. This is especially true in the aerospace industry and in the military transport industry.

Almost twenty years after the inception of CFM on crimping presses in the automotive industry there is now an opportunity to implement a Crimp Quality Monitoring system on manual hand tools. Such a development would be useful for the wider electronics industry also. This research project aims to address this very issue where the author believes that there is a unique opportunity to develop a fully-fledged CFM system right onto an individual manual hand tool. A few years ago this concept may not have been feasible, but today with the volume availability of high-end, low-power microcomputers, with good memory capacities, the time is right to explore the feasibility of developing CFM for hand tools.

In the context of this thesis the standard crimp quality requirements for the manufacturing industry are briefly presented. The background to crimp force monitoring concept is discussed and its proposed suitability to a hand-driven crimp system is presented. Subsequently, the development and functionality of a proposed new Crimp Quality Monitoring system for manual hand tools is presented, where the system is evaluated and the results are presented.

1.2 Rationale for the Project

In the field of Electronic Engineering, wire crimping is a popular method to achieve a homogenous, permanent connection of a conductor and a connecting component. Good quality crimp connections guarantee a high level of electrical and mechanical reliability. In the automotive industry it is common practice to produce crimp connections by using fully-automated or semi-automated cable processing systems. In contrast, within the aircraft industry, a high number of cable connections are produced by hand. In both the aerospace industry and the military vehicle industry, the production of wire harnesses is partially processed by hand [3]. Since the reliability of the crimp connections is so important the quality issue goes far beyond the production industry. The quality level is also of concern in the product repair and service sectors. So the question arises; asking how can anyone ensure a long-term acceptable quality level, especially in cases where very complex contact elements are used? In part answer to this question, the aircraft industry to date does not accept automated crimp quality inspection on the deployed hand tools, so it relies on 100% visual inspection. This research work investigates an automated solution in relation to the use of hand tools that can avoid the necessity for such a 100% visual inspection.

The above stated background has led to the concept of the development of a Crimp Quality Monitoring system for manual hand tools, which would have the ambitious goal of being able to guarantee that only good quality crimped parts are accepted in a wire harness assembly. The proposed solution would be a universal solution that would have the potential to be used in a variety of application fields and use cases.

1.3 Project Objectives

This research project is part of a new project venture for the company SLE electronic GmbH. SLE is regarded as the inventor of the crimp force monitoring scheme, since the beginning of the 1990s. The logo of the company can be seen in Figure 1.1.

Figure 1.1: The company logo of SLE electronic GmbH

SLE electronic GmbH, headquartered in Grafenau, Germany, is the project leader for the ongoing research and development of CFM systems.

The main focal point in this research project work is on the processing of tubular crimp connections, produced by the employment of manual hand tools. In the course of the experimental work, tool devices are developed and their use and effectiveness are analysed and assessed in a proper experimental manner, so as to learn meaningful information about the actual crimping process. One end goal is to realise a practical tool that can be used in any relevant industry. To achieve this, a key objective will be to learn specific information about the actual crimp force characteristics. Various special algorithms are explored and evaluated experimentally. The realisation of a prototype tool requires research and assessment of different solutions so as to establish the best design choices for the sensors, the microcontrollers, and the overall application kit for a full system.

Figure 1.2 shows the individual principal project goals.

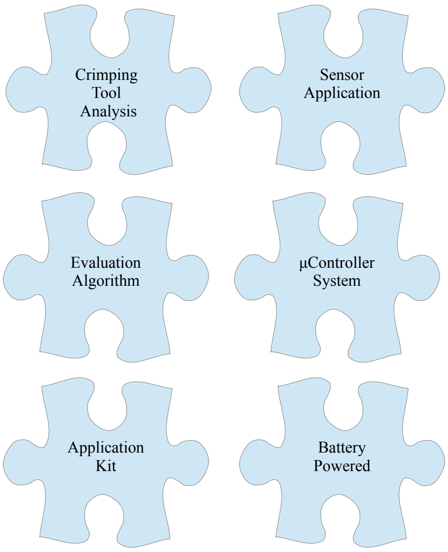


Figure 1.2: Principal project goals

The basic intention of the development work is to use state-of-the-art technology where possible, which can be readily applied to industrial applications with good economic benefits. The specific objectives of this research work can be stated as follows:

- Review the current research status in the areas of wire crimping assembly for electronic production systems
- Define the requirements for a new concept that will establish full CFM capability right onto a hand tool
- Evaluate the optimum solution to meet the requirements including choice of sensors, processors, signal processing circuits, statistical algorithms etc.
- Develop a prototype instrument and an evaluation system, which is applicable for all types of hand driven crimp tools
- Define the optimal process to meet the best practice for a Crimp Quality Monitoring system
- Conduct relevant experiments and test cases for validation of the concept
- Analyse the various results and report/publish the information

1.4 Novelty of the Project

As already discussed, a key novel aspect of the work defined here is the focus on manual hand tools that will yield a predictable crimp joint quality.

Prior to this research project, a comparable hand-tool crimp system, which can analyse the quality of a crimp connection in real-time, did not exist. Very expensive ultrasonic and X-ray instruments are currently used for non-destructive quality assessment of crimp joint production. Such quality assessment measurements take a significant time to evaluate whether the product is good or bad.

Since the introduction and usage of aluminium wires and terminals in the aerospace industry there has been an increased need for crimp joint quality monitoring due to the more sensitive material behaviour for aluminium crimp processing. At the current time the majority of such terminations are quality-controlled by operator visual inspection, but this can lead to a high rate of undetected errors due to the human repetitive attention error.

1.5 Literature Survey

Many of the topics, which are fundamental to the task of describing the current practices and methods for the production of crimp connections, were researched. A deep understanding of production quality requirements needed to be gained. The best sources of information for these topics were found in the various industrial and military standards [4] [5] [8] [11] [12] [13] [14]. The ‘IPC/WHMA-A-620’ [4] was fundamental in understanding the general requirements of wire harness assemblies. Volkswagen’s group standard ‘VW 60330’ [5], as well the IEC’s industrial norm ‘60352-2:2006’ [8], are the determining standards in the European automobile manufacturing industry, related to crimped wire connections. The ‘ECSS-Q-ST-70-26C’ [11] defines the quality requirements especially in the field of aerospace products. Considering the American car industry, the Society of Automotive Engineers with its specifications [12], [13], and [14] are relevant to become acquainted with the relative practices to assure crimped quality.

To understand how the industry quality claims are being met, the specification of current machines and equipment needed to be researched. Very useful documents were found at the homepage of Assembly Magazine [15], and in particular means the published reports [3] [7] [10] [16] were very useful. The article ‘Terminals for Terminators’ [3] helped to understand the employment of crimped cable terminations in the highly sophisticated field of military transportation. The articles ‘Crimped Loose-Piece Contacts’ [7] and ‘Assessing Crimp Quality’ [10] comprise the basic information of how to handle bulk material and what are the current methods to prove good quality. ‘Terminating Wires Efficiently’ [16] presents the today’s demands of cable mass-production. In addition, many of the technical specifications detail of the production equipment was provided by the relevant company documents [6] [9] [17] [19]. The presented ‘Quality Crimp Handbook’ [6] and ‘Wiring-Installations-Supplies: Cable crimping: choosing the right equipment’ [9] provide equipment specifications in regards to common crimping tool techniques, whereas, the product leaflet of SLE quality engineering GmbH & Co. KG [18] ‘CRIMP PRESS – SL P2000 SERIES’ [17] helped to get an technical insight into a very typical crimping machine. The best information about Piezo-sensors was found at the homepage of PCB Piezotronics Inc. [19].

In attempting to exhaustively understand the functionality of the current applied crimp force monitoring schemes, the main sources of interest were the technical documentation of the company SLE quality engineering GmbH [23]. A patent from Tyco Electronics [24] was very informative.

For the development of a new sensor system, to sense the surface elongation of loaded materials, a deep understanding of strain gauge technology needed to be gained. The guide ‘Eine Einführung in die Technik des Messens mit Dehungsmessstreifen’, was found to be very useful. To process the sensor signals in the most suitable and practical way, the state-of-the-art methods of low-voltage signal processing were researched. For this the best documents were the various datasheets and application notes from Semtech Corporation and Analog Devices Inc. [26] [30] [31].

During the microcontroller development phase the official website of NXP [33], and the documents [32] [35] provided there, proved to be very useful to learn and understand the microcontroller’s complete range of functionalities. A detailed description of the real-time operating system that was used is found in information from Keil GmbH [34].

Finally, to determine the best approach to test and validation, it was necessary to study approaches to properly establish, in a practical way, how to statistically assess the functional quality of the various features. The JCGM standard, ‘Guide to the expression of uncertainty in measurement’, was studied and this was found to be most informative [39].

A full list of reference material can be found in the Bibliography section of this thesis.

1.6 Structure of the Thesis

As many engineers will not be familiar with the narrow, specialised field of current practices for crimping cable termination, and its criterions of assuring the product quality, Chapter 2, ‘Current Practices and Methods for Produced Crimp Connections’ provides a short overview. This chapter also describes the various applications in automotive and aerospace engineering according to the IPC/WHMA-A-620 [4] and VW60330 standards [5].

In order to determine the work packages for this research project it was essential to get a comprehensive overview of the ‘Review of State-of-the-Art CFM/CFA’, which is presented in Chapter 3. Here it is explained how the individual components are integrated into the production equipment. Furthermore, the essence of this chapter is a description on the basic functionality of a crimp force monitoring (CFM) system in terms of signal conditioning and evaluation.

The development of the proposed tools feature, and indeed the system, is based on various system requirements and on the availability of sensing components in the market. Chapter 4, ‘Development of the Tool’s Features’, outlines for the designer how the various beneficial parameters were decided upon, such as the sensor components and the individual technical approaches. The software components for the realisation of the project are of key importance and this development is described.

Chapter 5, ‘The Measurement Process’, as the name implies, describes the digital processing of the measured raw data, as well as their statistical evaluation.

To process the various signals and to process the statistical algorithms in real time, the developed system requires intelligence. Chapter 6, ‘Development of the Tool as a Full Instrument Device’ outlines the selection and the application of the defined hardware components. Further, the printed circuit board is described, not exhaustively, but in sufficient detail to understand the defined requirements.

Chapter 7, ‘Prototype Construction, Evaluation, Validation and Testing’ concerns the testing and validation of the developed system. There is a description of all investigated test cases for the various hardware and software features.

A summary of the work carried out in this research project is provided in the final chapter of the thesis, Chapter 8, ‘Conclusions and Continuation Work’. Some ideas for the further development of a Crimp Quality Monitoring scheme based on hand-tools are proposed in this chapter.

1.7 Summary

This chapter describes some background the development of the process quality control for crimp connections. The background for crimp termination practice in industry has been summarised along with a description of the quality assurance practices, which are based on the industrial standards IPC/WHMA-A-620 [4] and VW60330 [5]. A short literature review was presented so as to provide sources for the various reference information.

2 Current Practices and Methods for Produced Crimp Connections

2.1 Introduction

Before any work can be initiated on investigating and developing a crimp quality monitoring system for manual hand tools, there is a need to provide a comprehensive overview of the produced crimped product processes, and the associated quality management policy. Those who are new to the topic are often impressed with the precision and sophistication of the practices, especially in the automotive industry and the aviation industry.

2.2 Objectives

This chapter aims to briefly introduce the general background of the applied crimping techniques that underpins the development of the CQM system. The topics discussed are intended to explain, in context, the various crimping materials and the related production equipment. This background will reveal the complexity and the variability that this technology involves.

2.3 General Background

Crimping technology has been around for a long time and is today the most popular method used, when a homogenous and permanent electrical connection is needed. The availability of sophisticated and automated cable processing machines is one reason why crimping is able to provide good process stability, and represents an economic way to produce a wire termination [6].

No matter whether hand tools, bench-top equipment or fully automated assembly-machines are used, crimping is the most popular termination technique in the wide field of transport electronics. This had many technical advantages, as long as the necessary quality assurance methods are adhered to.

For example, to achieve or to maintain high quality levels, the German original equipment manufacturers (OEM) for the automotive industry have established a brand-crossing standardisation in regards to the testing and processing requirements for crimped connections [6]. In general, there are three key elements to consider: the terminal, the wire, and the related tooling.

In this research work on crimp quality monitoring, it is important to bear in mind that the most relevant choice of crimp processing tool always depends on the type of the terminal being used. In some circumstances, this can imply that one can use an already existing CQM method or, in other circumstances, it might be the reason for the development of a new CQM technology.

Due to the focus on the importance of the type of crimp terminal, in the following subsections only the crimp terminals are going to be considered.

2.3.1 Terminals

For this research work, the differences between crimp terminal types need to be understood. This is because the greatest demand for the CQM feature on hand-tools is largely driven by the need to process special types of terminals. In addition to this, some special type terminals, or multi-component terminals, are usually constructed as bulk material, which is mostly handled by manual crimp tools.

In general, the more complex terminal architectures give rise to greater costs.

All production managers know that a high reject rate for any part on a production line leads to a high production cost expenditure, and can possibly compromise end-customer quality.

This is why there are very high expectations in the use of hand-processing crimp tools for high-priced contact elements. The hand process is expected to achieve the same technical capabilities and quality, as exists for automatic machine assembly.

2.3.1.1 Open Crimp Barrel Terminal

In an unprocessed state, open barrel terminals (OBT) have a crimp area, which is opened on the upper side. The typical cross-section model contour is U-shaped or V-shaped [5].

The production method used in their manufacturing is stamping and forming technology, which provides the big advantage that the terminals can be produced as reeled and striped material at a high process speed. This means that each single contact element is separated by the same distance, or pitch. This leads to very comfortable product handling for any processing solutions [5].

The wire is placed in between the U-shaped or V-shaped contour, so the crimping operation simultaneously closes the open barrel wings, while separating the contact element from the transport strip [5].

Figure 2.1 illustrates an open barrel crimp connection, from the Quality Crimping Handbook - Molex Inc. [6].

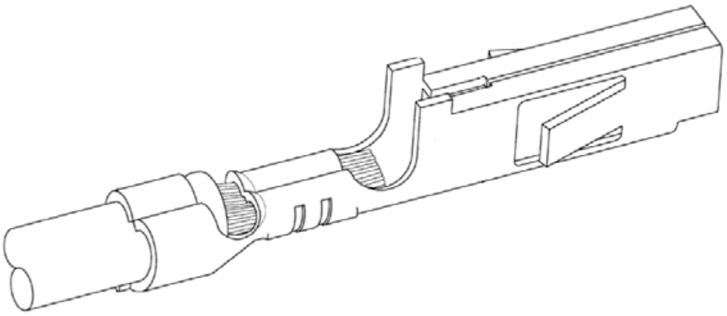


Figure 2.1: Open barrel crimp connection **[6]**

The typical cross section shape of the conductor crimp of an open barrel terminal is given in Figure 2.2. This is called a ‘F-Crimp’ or a ‘B-Crimp’, and this currently it is the most common crimp contour used for stamped and formed terminals [5].

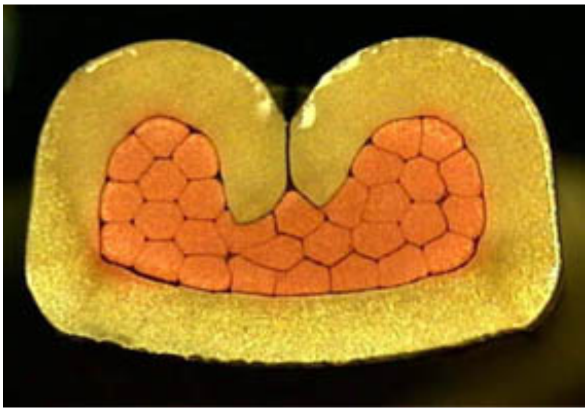


Figure 2.2: ‘B-Crimp’ microsection of an open barrel terminal crimp

In the majority of cases, open crimp barrel terminals are processed using bench-top crimp-presses; or similar cable-assembling machines with an integrated, automatic terminal feeder. In current practices, production machines, such as bench-top crimp presses for the production of reeled stamped and formed contacts, are initially equipped with integrated crimp force monitoring systems.

Thus, the main focus of this thesis is on the processing of closed barrel terminals.

2.3.1.2 Closed Barrel Terminal

In contrast to open barrel terminals, closed barrel terminals (CBT) have a closed crimp-contour, which is comparable to a hollow cylindrical body in which the stripped wire end is going to be inserted. Based on the particular manufacturing practice, closed barrel terminals are also called ‘screw-machine contacts’ or ‘turned contacts’. In contrast to stamping and forming, the production of CBTs is very expensive. In addition to this, their high processing-quality level also accounts for the high price [7].

Furthermore, the CBTs are usually packaged as bulk material or loose piece contacts (LPCs), which negatively impacts on the complexity in the process handling.

Figure 2.3 shows a typical screw machine contact, which is terminated on a wire. This figure is from the standard: ‘Requirements and Acceptance for Cable and Wire Harness Assemblies’, IPC/WHMA-A-620 [4].

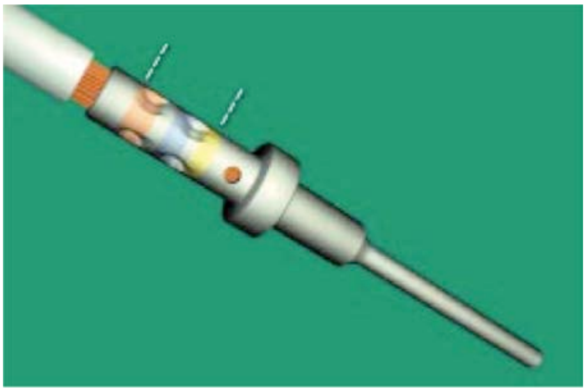


Figure 2.3: Closed barrel terminal crimped on a wire **[4]**

Due to the high price and the complex of processing capabilities, LPCs are only used in application fields where very high quality terminals are required, such as the military transport industry or the aerospace industry.

The precise cylindrical geometry of the LPC enables a perfect fitting between a male and a female connector and gives mechanical and electrical advantages, as compared with OBTs, as follows:

- A very low transition resistance
- Less temperature rise
- Resistant to disconnections caused by vibrations

Further advantages over open barrel terminals include savings of space and weight for the formed end products, due to the very small closed barrel terminals, with the equivalent electrical characteristics of OBTs, but in a smaller size [7].

The cross-section contours of typical closed barrel terminals, after crimping, are presented in Figure 2.4.

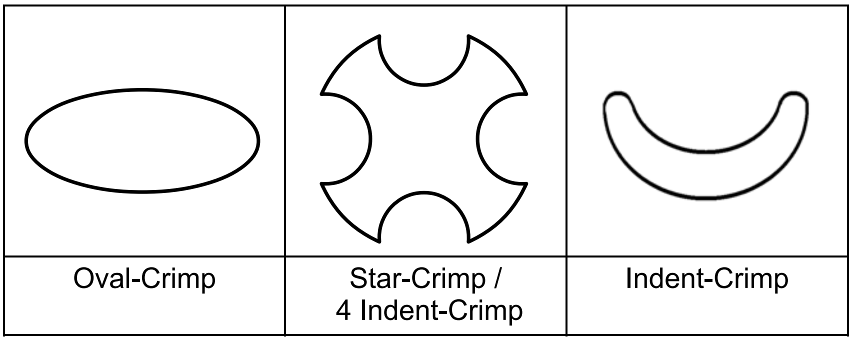


Figure 2.4: Typical microsection shapes of closed barrel terminals

The most reliable crimp contour is the ‘Star-Crimp’ in which four indents are made at 90 degrees to each other [8]. This 4-indent-type crimp can accommodate a wider variety of conductors in a given fitting. This means that various wire diameters, with the related crimp-depth, can be processed using the 4-indent crimping mechanics without any component changes [9].

Figure 2.5 shows an almost ideal ‘Star-Crimp’ microsection analysis.

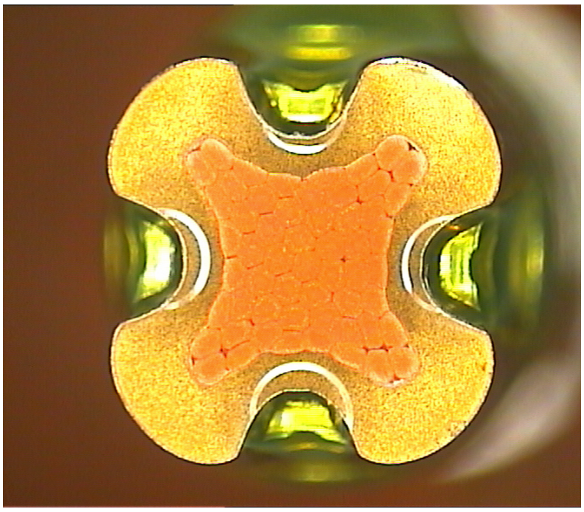


Figure 2.5: ‘Star-Crimp’ microsection of a closed barrel terminal crimp

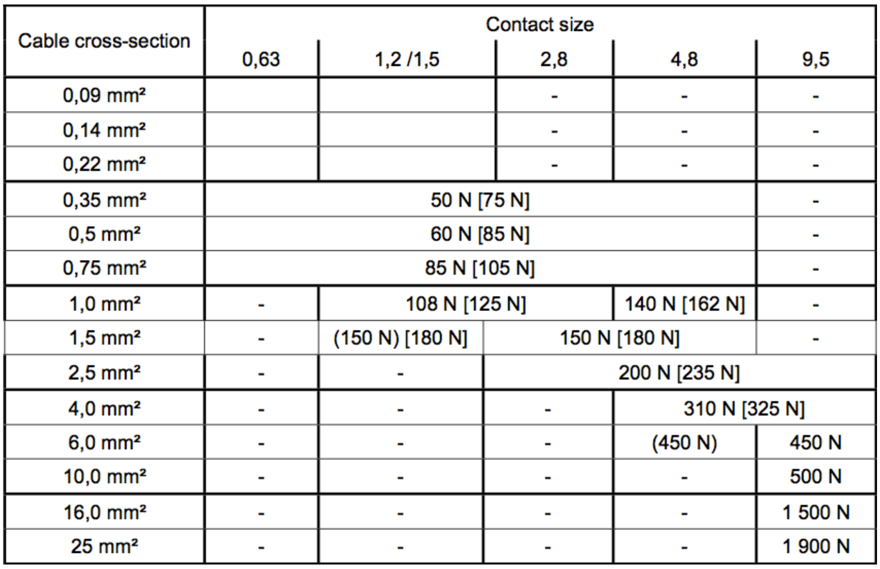
2.4 Quality Criterions

The integrity of a crimp junction can be characterised in three major feature categories:

- Mechanical stability
- Electrical properties
- Thermal reliability

This sort of characterisation includes, for example, a crimp junction with a high conductor-extraction force and a low electrical transition resistance [8].

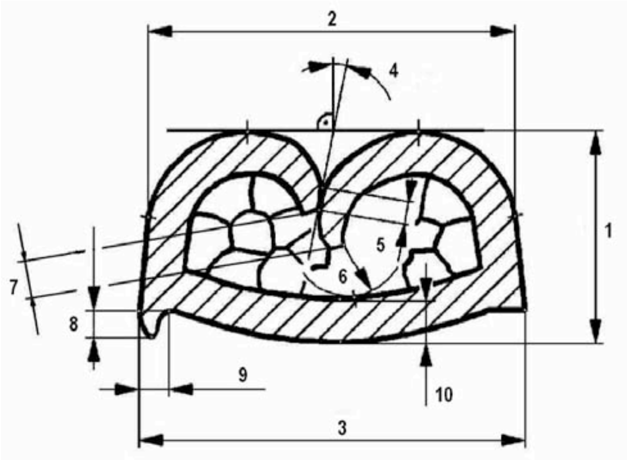
The testing practices for crimp junctions can principally be classed into: 1) destructive measurement, and 2) non-destructive measurement. Table 2.1 shows the specification of ‘Conductor Extraction Force’ according to the ‘Volkswagen Crimp-Norm’ [5].



Cable cross-section	Contact size				
	0,63	1,2 /1,5	2,8	4,8	9,5
0,09 mm²			-	-	-
0,14 mm²			-	-	-
0,22 mm²			-	-	-
0,35 mm²	50 N [75 N]				-
0,5 mm²	60 N [85 N]				-
0,75 mm²	85 N [105 N]				-
1,0 mm²	-	108 N [125 N]		140 N [162 N]	-
1,5 mm²	-	(150 N) [180 N]	150 N [180 N]		-
2,5 mm²	-	-	200 N [235 N]		
4,0 mm²	-	-	-	310 N [325 N]	
6,0 mm²	-	-	-	(450 N)	450 N
10,0 mm²	-	-	-	-	500 N
16,0 mm²	-	-	-	-	1 500 N
25 mm²	-	-	-	-	1 900 N

Table 2.1: ‘Conductor Extraction Force’ specification as per ‘VW 60330’ **[5]**

In current practices, many specifications and quality parameters are measured by instruments such as an outside micrometer. These can be simple parameters such as the ‘Crimp Height’, ‘Crimp Width’ or other mechanically measurable values. In addition to this, there are some electrical parameters, such as the ‘Contact Resistance’ or ‘Dielectric Strength’, which also describe the quality state of the crimp connection [8]. One of the most important techniques to establish whether a crimp junction is good or bad, is to do a micro-section analysis [10]. Using the correct micro-section laboratory analysis, a statement concerning ‘Gas Tightness’ or ‘Compression Ratio’ is possible. Optical measuring of a micro-section image, using a calibrated measurement display graph, under a ‘Graphical User Interface (GUI)’ on a PC, can be an optional substitute for mechanical, dimensional measuring. Figure 2.6 presents the typical dimensions of a ‘B-Crimp’ contour, which is determined by the ‘Volkswagen Crimp-Norm VW60330’ [5].



Legend

1	Ch	Crimp height
2	Cw	Crimp width
3	Cwm	Measurable crimp width
4	Sa	Supporting angle
5	Hs	Supporting height
6	Fc	Face end clearance
7	CFE	Distance between crimp face ends
8	Bh	Burr height
9	Bw	Burr width
10	Sb	Base thickness

Figure 2.6: Dimensions of a typical ‘B-Crimp’**[5]**

All of the relevant parameters are described and defined by the appropriate agreed standards, which are provided by the terminal manufacturers, OEMs, technical institutes, committees and engineering associations, such as the ‘Volkswagen Group’ [5], or the ‘International Electrotechnical Committee (IEC)’ [8]. Usually, these standards are applicable, overall, to the various industry categories. However, there are also some publications that affect just individual industrial sections. Table 2.2 shows an example for the differentiation in standards between the automotive industry and the aircraft/military industry. Due to the restricted regulations in this scope of engineering there is no difference between aerospace standards and military standards [4], [5], [8], [11], [12], [13], [14].

STANDARDISATIONS	INDUSTRIAL SECTORS: automotive	INDUSTRIAL SECTORS: aircraft / military
SAE/USCAR 21	✓	
VW 60330	✓	
IPC/WHMA-A-620	✓	✓
IEC/60352-2	✓	✓
SAE AS22520		✓
SAE AS39029		✓
ECSS-Q-ST-70-26C		✓

Table 2.2: Various cable-processing standardisations in terms of industrial sectors

Across all of the individual standards, which describe the quality assurance for the production of cable terminations, there is a single common topic, which overlaps them all. This is the Crimp Quality Monitoring scheme. In particular, published papers, for example the group norm VW60330 [5] from the automotive industry, promote the crimp force monitoring scheme, as a proven in-line, quality assurance system for power-driven crimp tools. In some reports, the crimp force monitoring scheme may not be named as such, but its use is implied with phrases such as: ‘recording traceability throughout the process…’ [11].

2.5 Fields of Application

As already stated in this thesis, there are various international standards and guidelines for ensuring the quality of the connection between a wire and a terminal. However, to establish which standard is most applicable for a particular product to be produced, there is a need to differentiate between automotive applications and aviation/military applications.

It is also most important to appreciate the effects of choosing an unsuitable quality management scheme. On one hand, for example, a company may be interested in mass production and is thus concerned that a quality system will avoid any potential enormous financial damage to the company in the event of failures, and on the other hand, a company might be highly rated for security and safety issues, and is more concerned that the quality system will guarantee the proper functionality of military vehicles; avoiding risks which can create personnel damage, or possible warfare related incalculable losses.

To put it in the words of Adam Cort, a senior editor for the Assembly Magazine [15]: “If you are driving a tank through the desert your main concern is that your wire terminal remains attached” [3].

2.5.1 The Automotive Industry

Due to stringent technical and quality requirements, rising production volumes, and the growing sophistication of the stamping industry, it is now even more popular to use stamped and formed contact material for the majority of applications in the automotive market [7]. As described above, stamped and formed crimping material comes on a reeled carrier strip, hence it is possible to use highly sophisticated automated wire termination machines.

The production of tens of thousands of cable connections in one day is not unusual in today’s wire-harness manufacturing facilities for the automotive industry [14]. Thus, some of the wire harness producers have established their own industry specifications, while others prefer to follow terminal standards such as IPC/WHMA-A-620 [4], [16]. The German automaker, Volkswagen Co., has published its own standard to instruct their suppliers on how they should test crimped terminals [5].

To assess whether the quality of a standard wire-to-terminal connection for the application of automobiles meets the requirements of the relevant agreed standard, usually three major testing methods are needed:

- **Crimp Force Analysis (CFA)**

The relative crimp-force is recorded simultaneously to the crimping process itself. Usually the transduction is presented as a force-over-time graph. The evaluation algorithm compares the recorded curve with a pre-stored reference curve [7]. (More details will be presented in Chapter 3)

- **Conductor extraction force measurement/pullout force measurement**

  According to the European Norm 'EN 60512-16-4' a wire pullout force measurement device destroys the crimped connection along the cable outlet by applying mechanical load. The extent of the measured 'force-value' provides information about the mechanical quality of the crimp termination [16].

- **Micrograph inspection**

  The produced crimp connection is cut at a defined position, right angled to the cable. Afterwards, the cut surface is grinded and treated chemically. An optical evaluation of the termination can be done. The equipment required includes: a zoom microscope, a digital camera, and a PC to provide the necessary graphical user interface for gauging the image. Some typical parameters of interest are the optical crimp height, optical crimp width (Figure 2.6), and gas tightness (to ensure that there is no void within the strands) [16].

2.5.2 Aviation / Military Industry

It can be assumed that the military and aerospace sectors are extremely stringent when it comes to the reliability of electronic equipment. Such equipment needs to sustain all the extraordinary challenges on land, at the sea, and in the air. Continuous vibrations, high humidity, pressure changes, or extreme high or low temperatures are just a few examples of the environmental stresses [3]. Cable connections, or cable junctions, are naturally affected by such conditions and thus need to be designed and processed to endure those environments.

Back in the 1940s, the military was exploring alternative solutions to the contemporary soldering method of creating wire-to-wire connections. As a result, crimping, as the mean of making a connection between a terminal and a wire, was initially developed by the military [3].

In terms of the type of connectors, the military generally prefers the closed barrel style with the old-fashioned, ring style, due to their good mechanical and electrical reliability. In respect to the crimping portion of the terminal, the most common implementation is a closed-barrel configuration. It is common to find terminals, which use very expensive, gold-plated connectors; as this, improves the electrical properties, especially for high-end technical applications [3].

In the majority of cases the terminal is a ‘screw-machine’ contact-pin as discussed in section 2.3.1.2. Such terminals are usually processed by hand, using appropriate hand-tools.

To assure good crimp connections, aircraft manufactures often classify the terminals into: 1) Class 1 terminals, which can only be crimped with an approved tool; and 2) Class 2 terminals which can be crimped by the use of more general tools, which are available in the marketplace [3].

The appropriate dies and crimpers for Class 1 terminals are defined by the SAE AS22520 specification (previously MIL-C-22520). However, all wire terminations, which are produced in compliance to this specification, also need to withstand destructive and non-destructive test procedures [3], [11]. The following points need to be adhered to:

- **Hand-tool calibration**
  Stipulated by quality specifications, the crimping equipment needs to be recalibrated and tested frequently.
- **Visual inspection**
  Every single connection needs to be visually inspected in detail by the operator. This usually takes up to two minutes.
- **Conductor extraction force measurement**
  This is the same procedure as used in the automotive sector.
- **Micrograph inspection**
  Micrograph analysis is carried out for the same quality assurance reasons as in the automotive sector.

2.6 Summary

This chapter has presented the basic background for crimping techniques and the associated quality assurance (QA) approaches, which are applied in the key manufacturing sectors. The current crimping techniques have been described, not exhaustively, but in sufficient detail to appreciate the information presented in the upcoming chapters.

An important conclusion is to state: crimp force monitoring was established for the automotive industry many years ago [10], but in order to adapt the same scheme into the aerospace and military industries, there is a huge financial and educational investment required to find ways to change the currently entrenched habits.

The next chapter focuses on the state-of-the-art crimp force monitoring (CFM) practices, which are established in the today’s automotive industry.

3 Review of State-of-the-Art CFM/CFA Practices

3.1 Introduction

As already stated in the previous chapters, existing technology is in use for analysing crimp force so as to precisely define the quality of a crimped electrical connection. This research proposes a new development for a crimp force monitoring (CFM) scheme, based on the study of the functionalities of the prior-art of CFM systems. In the context of the actual wire harness branch, crimp force monitoring (CFM) and crimp force analysis (CFA) will be considered as a single topic.

Rather that attempt to review the huge number of individual technologies in the market place, a comprehensive general review can be presented, as the majority of existing CFM systems are based on common fundamental concepts.

3.2 Objectives

The objective of this chapter is to present a comprehensive background to the state-of-the-art technology of crimp force monitoring. An additional goal is to present the basic functional practices that explain how the measured data is evaluated.

3.3 Basic Functional Principle

3.3.1 Setup

The existing crimp force analysis (CFA) schemes are most often used with frame crimp presses, where the press’s movement occurs between two upstanding legs. This type of crimping machine is typical for the processing of standard crimp terminations; they are available as bench-top versions (Figure 3.1). Also, the scheme can be integrated into an automated assembly line.

Figure 3.1: Bench-top crimping press **[17]**

In putting a crimp force monitoring system into operation, three components need to be considered for implementation into the crimping machine:

- Force sensor
- Movement sensor
- Evaluation module

Figure 3.2 shows the crimp force monitoring setup as a schematic representation.

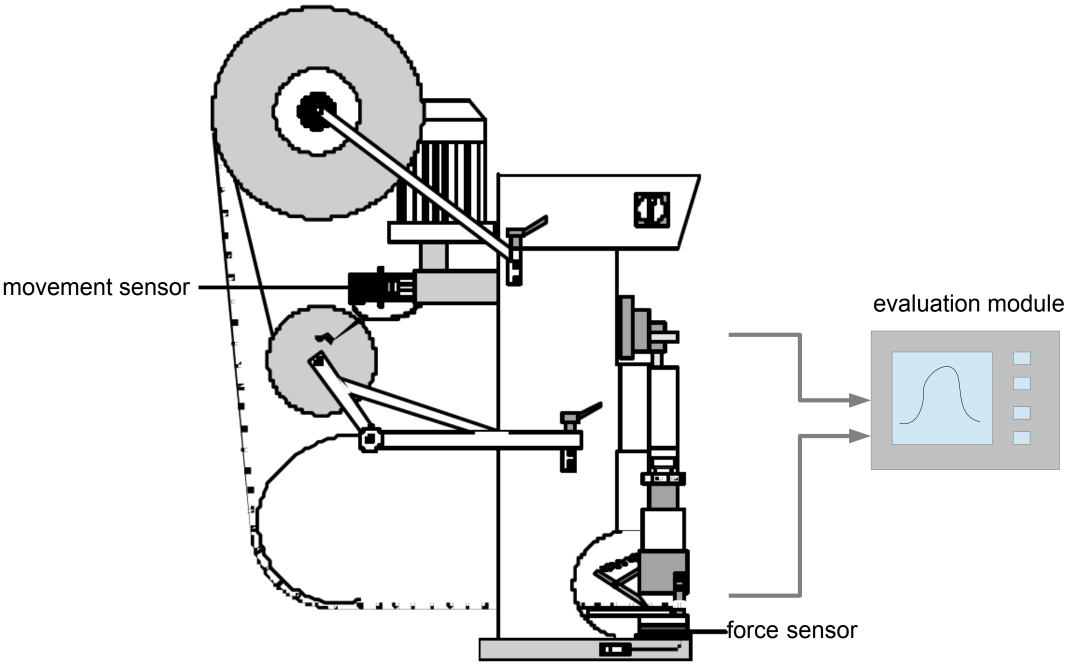


Figure 3.2: Crimp force monitoring setup **[18]**

During the crimping process the force sensor measures the applied mechanical load on the terminal. Subsequently, the movement sensor detects either the beginning of the movement, or it measures the total movement. Thus, the main task of the evaluation module can be described as a means to combine and condition the two sensor signals in a way that properly characterises the crimping process.

3.3.2 Performance

Simply measuring two sensor signals is not a sufficient activity to allow the making of a valid statement regarding the performance of a crimping process. This means that a crimp force monitor needs some additional predetermined data, in order to be able to rate the measured values. This is to say that the crimp force monitor needs to be specially configured. A common approach is to set the device into ‘learn mode’ at the beginning of production and to record up to ten identified ‘good crimps’ as a reference for process data. From this data an average-reference crimp curve is generated, which is used for comparing the subsequent records. In this way, the primary function of a CFM system is to evaluate, in a relative sense, the repeatable quality data, and to recognise whether there are significant variances in data with respect to the reference. There is a big advantage here in that it is not just the wire termination that is controlled, but disturbances of the whole system setup can be inherently detected. The data can be influenced by many factors, such as: by the operator using worn-out tool components, fluctuations in temperature, and by the use of some incorrect material. Figure 3.3 illustrates the influences graphically [18].

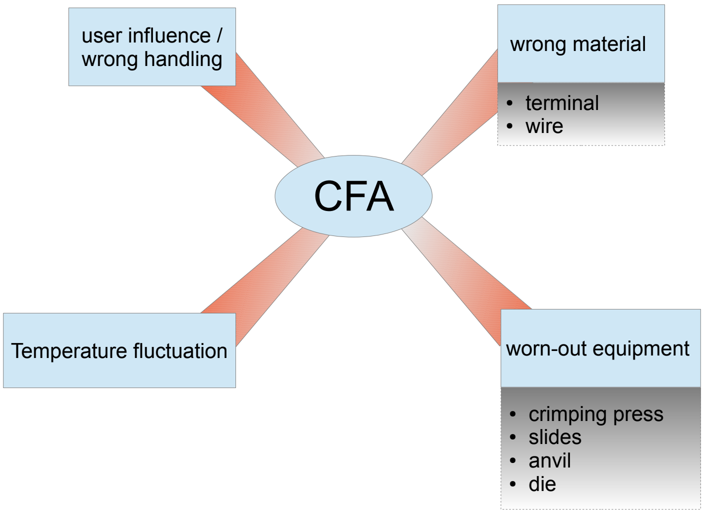


Figure 3.3: Influences on the crimp force analysis **[18]**

3.4 Sensor Components

The key measured value is the force that is derived for the mechanical load onto the process. Some CFAs provide two evaluation characteristics: a typical ‘force-over-time’ interpretation as well as a ‘force-over-angle’ (distance or stroke) dimensioning. The applied evaluation will depend on the type of sensor.

3.4.1 Force

The force measurement is usually achieved by the use of Piezo-electric load cells. They are typically applied in two different styles. Figure 3.4 shows both: the frame-style and the ring-style, as published by PCB Piezotronics Inc. [19].

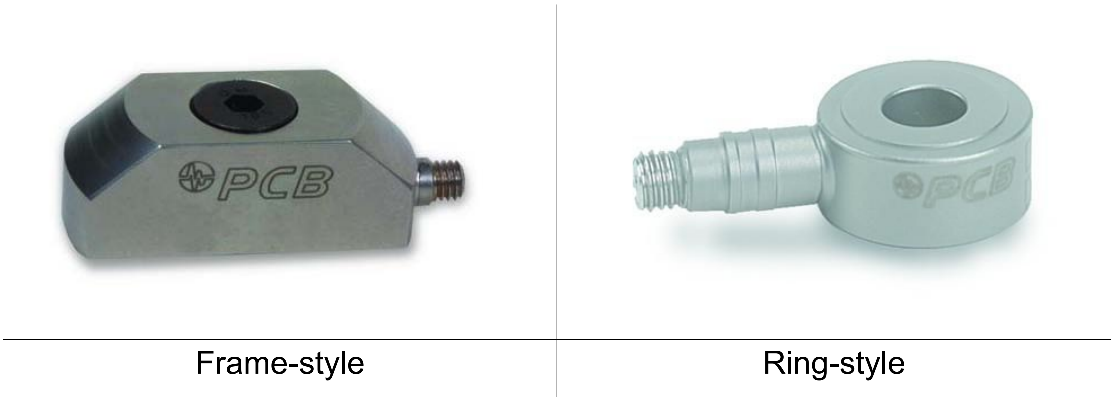

Frame-style
Ring-style

Figure 3.4: Piezo-electric force sensors **[19]**

It should be noted that the frame style sensor is the most common type due to its easy integration, i.e. it is simple to install in a press's frame by drilling just a single hole.

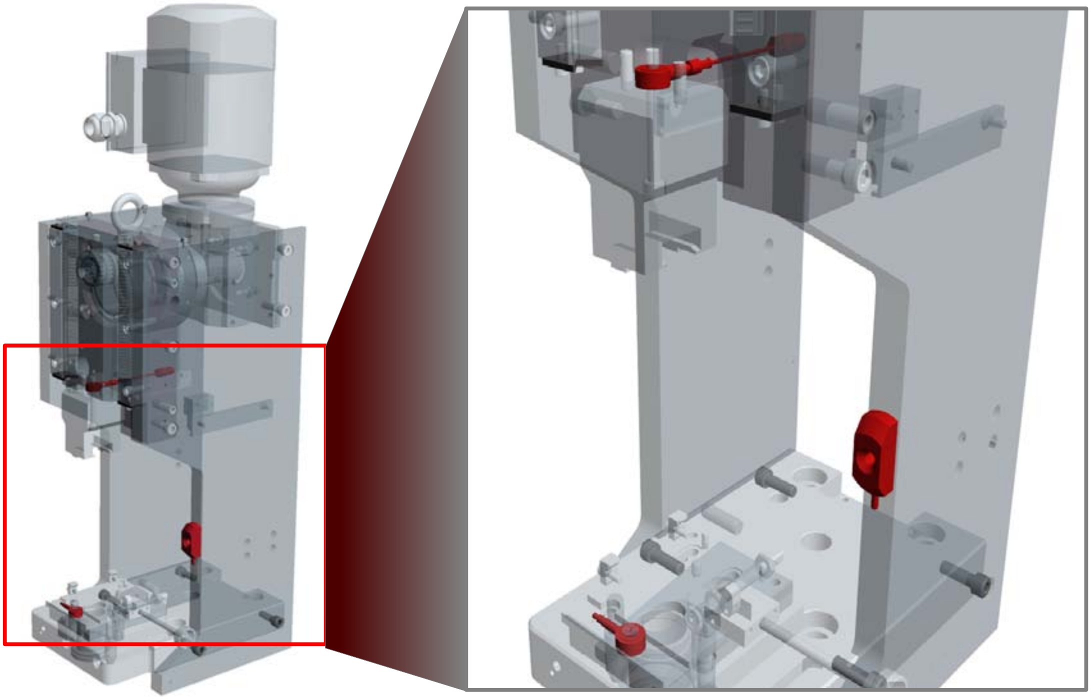


Figure 3.5: Force sensor positions on a frame crimping press **[18]**

Figure 3.5 shows some possible force sensor positions on a common frame crimping press. The upper red element represents a ring-style sensor, placed in the tappet of the press, whereas the lower red ring-style sensor shows the position for a base plate installation, and the third red-spotted item represents the frame-style sensor.

The frame sensor measures the press frame's surface strain, which results from the material tension caused by the mechanical load of the crimping process. The ring-style sensor measures the mechanical load, either in a direct line with the pressing force in the tappet, or slightly misaligned in the base plate [20].

Each individual sensor type has its own use cases and applications. Table 3.1 provides a comparison of the related assets and drawbacks, which are focused on the ergonomic handling of the installation, the expense factor, attrition resistance, and also on the sensitivity of the signal transduction.

	ring style		frame style
	ram	base plate	press frame
ease of installation	−	−−	+
affordability	−	−−	+
attrition resistance	−	+	++
sensitivity	++	+	−−

Table 3.1: Comparison of Piezo-electric force sensors **[18]**

As stated above, the big advantage of a frame-style sensor is the straightforward implementation, whereas a ring-style sensor type usually needs additional parts to enable the assembly. As a result, the base plate position always requires some propriety mechanical components. This also has an effect on the affordability, i.e. additional parts imply additional costs. However, ring-style sensors are fundamentally more expensive as compared to the frame-style sensor, not least because of their design. Ring-style sensors placed in the tappet are always in motion when the crimping press is acting, i.e. the attached sensor cable is also moving. Basically, the junction between the cable and the sensor is a typical wear part, which needs to be renewed, over time. But, due to the already stated fact that the ring-style sensor is in line with the press's movement, the sensor signal is much more precise as compared to the frame application [20].

3.4.2 Trigger

The typical 'force-over-time' assessment is the most common approach to evaluate the quality of a crimping process, but in addition to this it is necessary to integrate a second sensor component to tell the CFM's evaluation module when to start and when to stop recording the data.

A very common and cheap method to trigger the data acquisition is to use a simple proximity switch, which is integrated in the press's moving mechanics at a suitable position. Figure 3.6 illustrates a typical proximity switch, from Bernstein AG [21].

Figure 3.6: Inductive proximity switch **[21]**

However, the most precise and reproducible way to trigger a crimp force monitoring system is to use an incremental encoder, which is mounted to the driveshaft of the crimping press. A typical incremental encoder is presented in Figure 3.7. This image is from DR. JOHANNES HEIDENHAIN GmbH [22].

Figure 3.7: Incremental encoder **[22]**

By the use of an incremental encoder, the process motion of the crimping press can be converted into a digital signal with a sufficient resolution to generate a highly reliable ‘force-over-angle’ (also called ‘force-over-distance’) signature. However, it is also the most expensive way to trigger a crimp force analyser [20].

3.5 Evaluation

Once the data is recorded by the use of the above described sensor components, the necessary signal processing operation can be performed. Different algorithms for crimp force monitoring systems are used in various commercial equipment items in the marketplace, but the fundamental principle of the algorithm is common.

The following elaboration is based on the functionality of the crimp force monitoring systems of the company SLE quality engineering GmbH & Co. KG [23].

3.5.1 The Crimp-Curve

Figure 3.8 shows a typical crimp graph progression, which was produced by the use of a crimping press as described above. Such arithmetic charts are usually drawn as a continuous line, but for a digital evaluation [24], only 230 sample measurement points are considered to be sufficient.

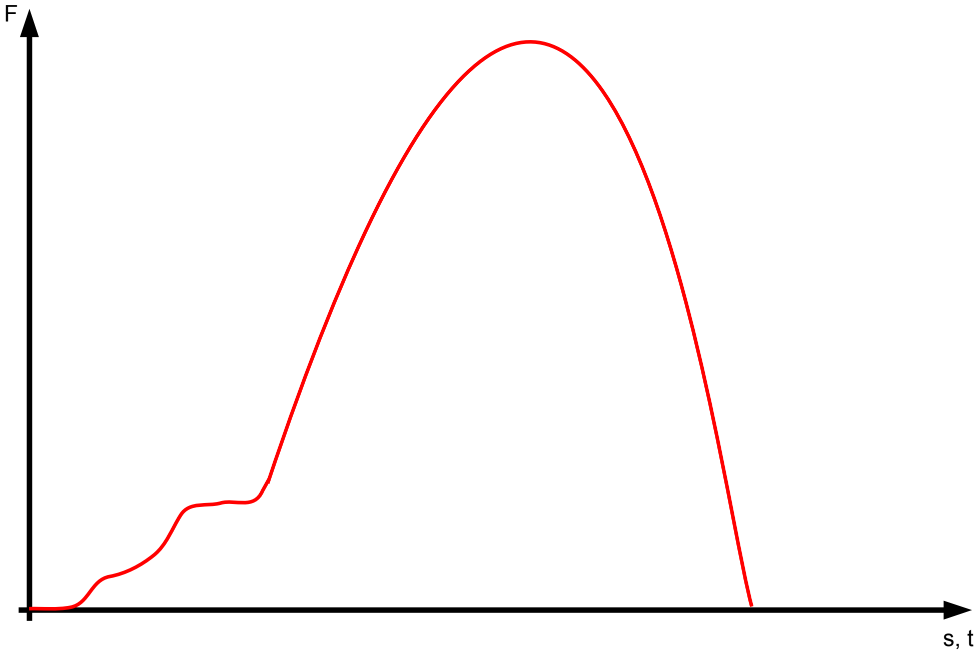


Figure 3.8: Typical crimp graph **[23]**

3.5.2 Filter Level

To avoid influences on the evaluation caused by noise or discontinuity, the lower part of the curve can be ignored by presetting a certain threshold value. This threshold is referred to as a filter level [23]. Figure 3.9 illustrates the filter level graphically [23].

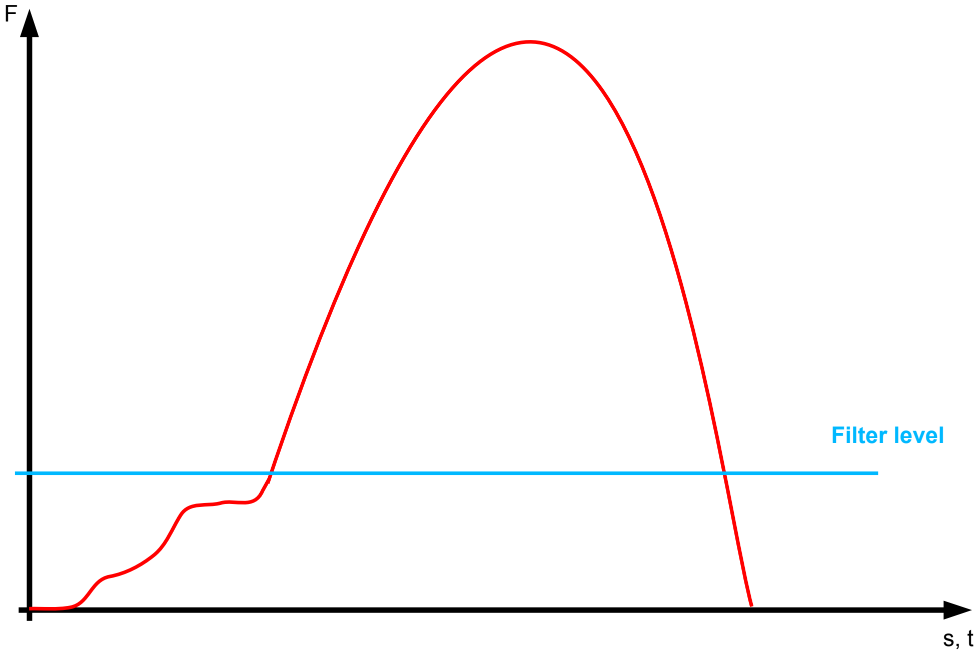


Figure 3.9: Filter level in a crimp graph **[23]**

This method is very useful to avoid some classical problems, which are consistent with disturbances in the lower force range.

3.5.3 Area Analysis

An area analysis algorithm determines the area, which is enclosed under the curve and above the cutting line of the filter level. Figure 3.10 represents this graphically [23].

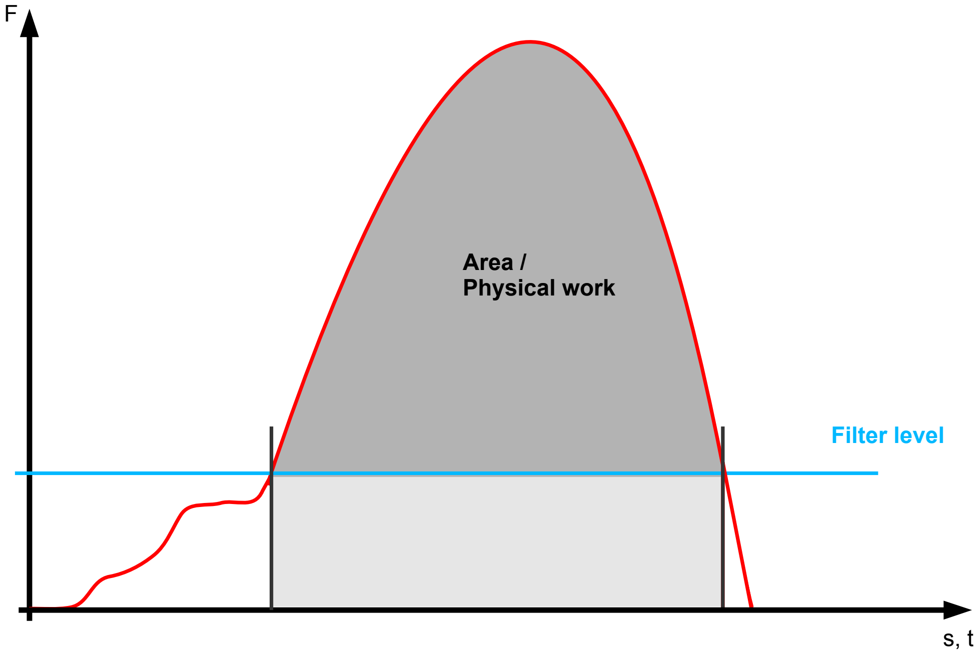


Figure 3.10: Crimping area description **[23]**

Once the CFM system is programmed with a predefined number of good curves, the calculated area is used for comparison with the subsequently measured curves.

There is an accepted variation in the measurement that is usually stated in percentage terms. A typical tolerance value in the automotive industry is +5% and -3% drift to the area value of the reference curve [5]. From a physical point of view, the outlined area can be considered as the physical work, and therefore the energy value, which was applied to produce a crimp connection [23].

This analysis method is especially useful to detect problems such as: use of incorrect materials, wrong wire size, misfit terminals, or worn-out crimping tools [23].

3.5.4 Shape Analysis

To analyse the shape of a recorded crimp curve, from the reference curves, two envelope curves are calculated, so as to define an acceptable error range, above and below a nominal curve. Figure 3.11 shows two envelope curves as dashed lines. The number of sample points is defined in the CFM's settings. Furthermore, Figure 3.11 points out the so-called area of interest (AOI). This parameter represents the range of curve values, which are located above the filter level and therefore affected by this digital evaluation. Hence, the combination of both: the AOI, and the shape of the envelope curves, provide the possibility to evaluate whether the recorded crimp curve is sufficiently similar to the reference curve, or not.

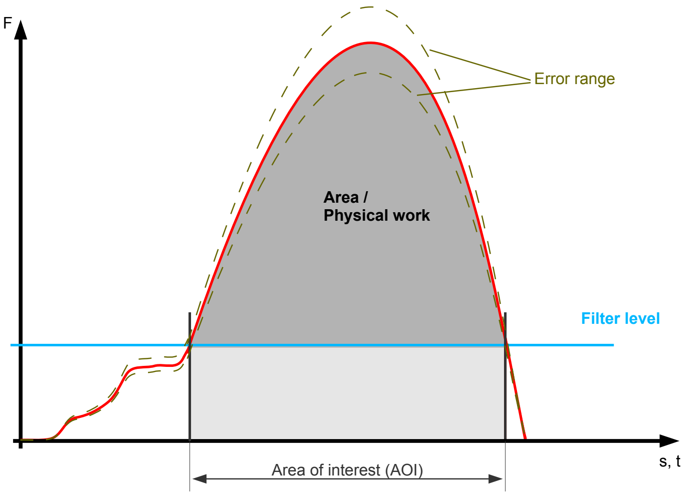


Figure 3.11: Shape analysis description **[23]**

This evaluation of the curve progression is a practicable method to reveal inconspicuous problem influences, such as partial insulation in the wire-crimp area [23].

3.5.5 Up-to-peak Analysis

The so-called 'up-to-peak analysis' means that the maximum force value, which the force sensor recorded, is considered as a worthwhile parameter for evaluation. Due to the experience of high variability of the measurements on the top of the curve, the actual peak force value is calculated as the arithmetic mean of the three highest measurement points. Figure 3.12 illustrates this circumstance [23].

This analysis method may be of interest when the crimping machine has no mechanical blockage while acting. This means that the crimping anvil and the crimping die have no physical contact while the crimping is being processed.

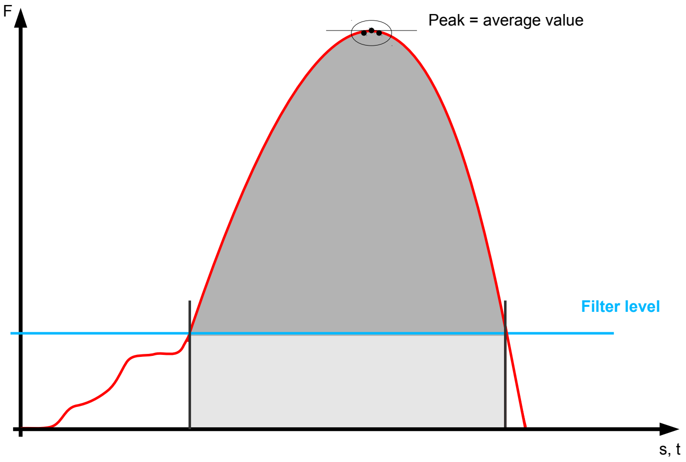


Figure 3.12: Up-to-peak analysis description **[23]**

3.5.6 Zone Analysis

To highlight partial segments of the crimp curve that are to be considered for evaluation, a CFM system usually provides the possibility of zone analysis. Still using the example of SLE's crimp force monitoring systems, Figure 3.13 shows the most exemplary and interesting zones of a crimp curve [23].

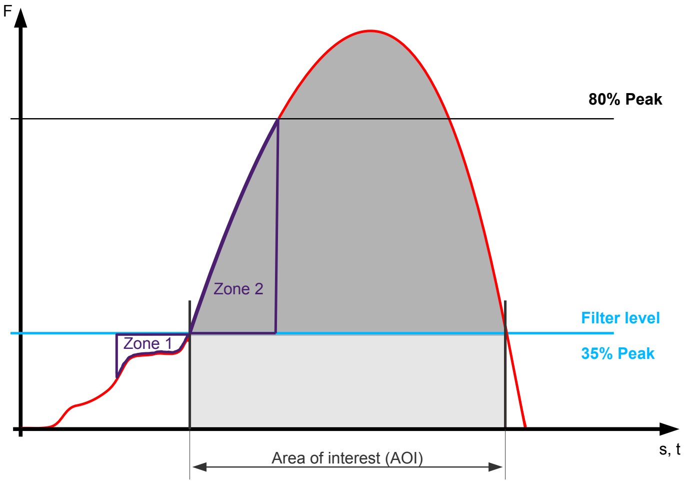


Figure 3.13: Zone analysis description **[23]**

Zone 1 is bounded below by the crimp curve and the filter level is the limit to the top. The limitation on the left side is given by an adjustable parameter.

The use of deformed crimp terminals can lead to an observed abnormality in zone 1, therefore the analysis of zone 1 helps to avoid some malfunctions, which are usually caused by defective terminals.

The area of Zone 2 as shown in Figure 3.13 [23] introduces a cutting line at 80% peak force. Observed abnormalities in this zone, based on experience, infers some typical inconsistencies; a good example being that of poor performance of the materials behaviour, where the terminal is affecting the conductor during the deformation [23].

3.6 Summary

This chapter has introduced the current state-of-the-art methods of crimp force analysis, which is applicable to sophisticated production machines in the wire harnessing business.

The basic concepts of crimp force monitoring, including the production machine, the sensor components, and the evaluation procedure have been described, not exhaustively, but in sufficient detail for the reader to understand why this setup needs to be freshly reviewed, towards the development of a new solution to enable the same quality control method of produced crimp connections to be achieved, but this time using hand tools as the processing equipment.

Based on the presented schemes and the experience gained, Chapter 4 describes the development and investigation of the features of a new CFM scheme, which is also adaptable to portable production equipment, such as hand tools.

4 Development of the Tool’s Features

4.1 Introduction

The majority of market-leading companies in the wire harness industry seem to assume that a crimp force monitoring solution, for production-quality portable and hand-driven devices, is not feasible.

Thus, when this research project was initially proposed it was seen as the rebirth of a concept for the use of portable equipment in the production of crimped connections, where the expected industry quality levels can be maintained.

Based on the market potential for wide scale industrial use, it is desirable to develop a system, which is familiar to the production operators, who know the existing technology for automated machines, and at the same time be successful in meeting some completely new requirements. The key goal of the proposed new scheme is to develop a solution that has a practical use, that might be adaptable to almost every hand tool.

This chapter provides a comprehensive insight into the specialised field of crimp force monitoring schemes for hand tools. The necessary requirements, the applied science and technology, and the employed hardware components are described in this section.

4.2 Objectives

The key objective at the inception of this project was to develop an intelligent function block, for hand held tools, which provides the features of a crimp force monitoring system. The project’s goals include the development of a prototype model to demonstrate the feasibility of the concept.

This chapter aims to introduce the approach, along with the related science and technology that builds the theoretical foundation for the desired function block and the resulting prototype. Based on this foundation, Chapter 7 will introduce the validation and the test setups for the scheme.

4.3 Requirements and Conditions

Before any development work can be carried out, it is necessary that all of the basic conditions and requirements be discussed in detail. The most important topics for such a discussion are: 1) the technical issues, 2) the financial consideration, and 3) the quality assurance requirements.

4.3.1 Technical

Figure 4.1 presents the technical requirements on a priority grading. There are two main aspects to the development effort in this project: 1) the measurement system, and 2) the functional block, which includes the processing unit. A key artefact is the embedded microcontroller system. It is important to predefine all required features at an early stage of the project, so as to avoid, or anticipate, any major technical limitations in a later, more advanced stage of the project.

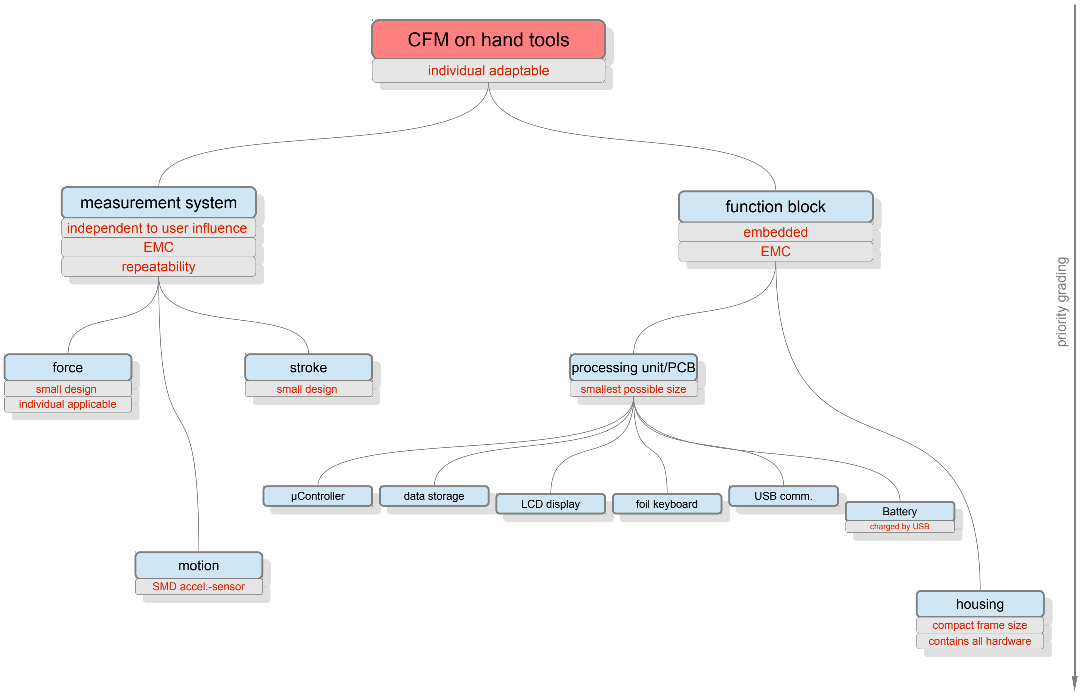


Figure 4.1: Technical requirements and conditions

An overriding technical requirement for this development work is the issue of adaptability; where a resulting solution can be applied to almost all kinds of hand tools.

The choice of the measurement system is paramount for specific applications, and therefore it is important to have consistency for the user experience throughout, so that there is a guarantee of a high-repeatability quality rate for any use case.

There are many other technical considerations to consider, beyond the stated functionality requirements. For example, the electromagnetic compatibility (EMC compliance) is a key element in respect to the development of a saleable product.

The engineering of a compact design for each individual sensor part enables a more flexible and manageable approach to the design integration for the mechanics of the crimping tools. In this respect the printed circuit board (PCB) should have the smallest possible geometrical dimensions, where each single element, as described in Figure 4.1, finds its place.

Towards the end of the priority sequence, as seen in Figure 4.1, the motion activity within the measurement system is listed. The measurement of the motion characteristics for the final product is very important, and it is suggested that the use of a surface-mount-device (SMD) acceleration sensor is desirable. This would be useful, for example, to detect any invalid physical incidents, such as an accidental crash on the floor. For the saving of energy, this acceleration sensor could also be used to provide an interrupt event to wake up the processing unit from stand-by mode.

Finally, a well-designed compact housing enclosure, which contains all of the components, is the final requirement in the development chain for this proposed crimp force monitoring solution for hand tools.

4.3.2 Financial

The financial considerations are very critical to the entire project, as a new manufacturing tool is being proposed, and all manufacturing organisations are heavily driven by cost considerations, in a competitive environment.

The current CFM solution, as described in Chapter 3, might have a typical price of about €2,500 per tool unit, whereas the price for a CFM scheme for hand tools would be much less.

The typical price of a crimping press, on which the current CFM scheme finds its main application, is about €7,500. Considering this price of the manufacturing machine and the price of €2,500 for a CFM system, the price relation, between the equipment item and the CFM solution, is approximately 3:1. Keeping with this consideration, a newly developed CFM solution for portable and small crimp tools should maintain this relationship of 3:1.

Hence, the target price for an add-on CFM system is about €500. To make a business proposition worthwhile, it will be necessary to achieve high volume sales for the proposed new product. To achieve good margins on such sales it will be very important to design the product to use low-cost materials, while still realising a top-quality product.

4.3.3 Quality

It is paramount to achieve a quality monitoring system in any newly proposed solution, which is capable of detecting critical failures in the production environment.

4.4 Sensing Elements

The initial link in the measurement chain, in assessing the quality process of hand crimp tools, is the determination of the physical parameters, using the relevant measurement elements, which combine to make up the autonomy of the entire system. The choice of the individual sensing elements is of utmost importance.

For the processing of crimped connections by the use of hand tools, it is the human operator who commands the control process. Hence, a repeatable ‘operation time’ cannot be guaranteed. However, to stay in line of prior-art for CFMs, this user influence needs to be taken into consideration. It is thus proposed that for this new scheme, an additional sensor component will be employed to sense the tool’s stroke; so as to realise a ‘force-over-distance’ measurement, which will help to guarantee the necessary repeatability.

The various sensors will be described. Further, it is proposed to use an integrated acceleration sensor to improve the feature list of the overall system, without having any direct influence on the functionality of the crimp force analysis. This will be achieved by ‘borrowing’ some concepts from the smart phone consumer product market, in particular the common feature of the acceleration sensor for matching the display's orientation when the smart phone is rotated from vertical format to landscape format.

4.4.1 Applied Force

In consideration of the product's requirements for high precision, good design, ergonomic handling, and competitive price, along with the need for sophisticated technology to assess the material's behaviour, it was decided to use a strain gauge transducer, as the best way to meet the demanding requirements.

A strain gauge scheme will form a solution to detect physical values, such as surface elongation, and convert such values into electrical signals. Typically, a strain gauge represents a bipolar passive ohmic resistor, which changes its resistance value relative to the deformations.

Figure 4.2: Principal strain gauge layout

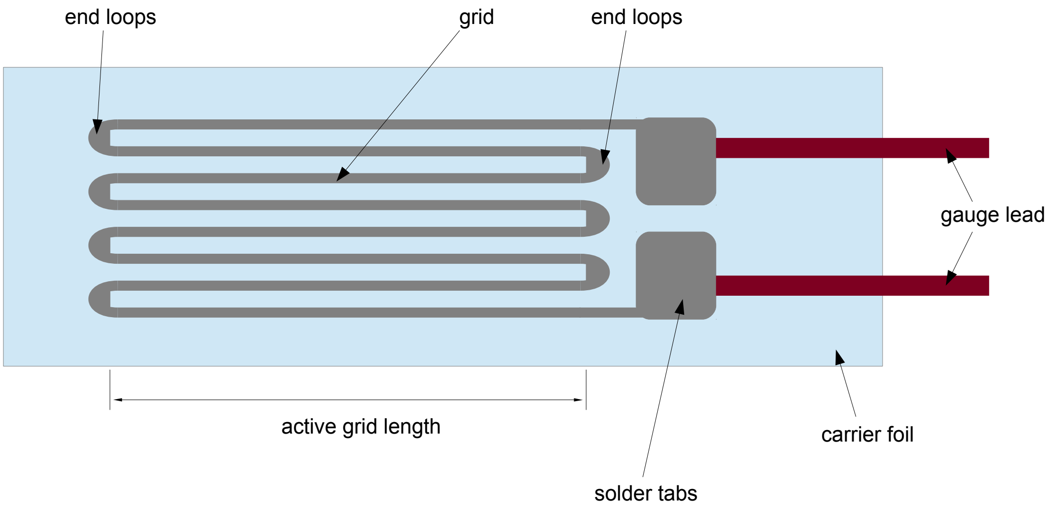


Figure 4.2 shows a strain gauge. The grid-material's specific electrical resistance defines the electrical resistance of the strain gauge in total [25], as follows:

$$R_{sg} = \rho \cdot l/A \tag{4.1}$$

R_{sg} = ohmic resistance of the strain gauge

ρ = material specific resistivity

l = length of the material

A = cross section area of the material

When a mechanical load stresses a mechanical element, the resulting material elongation, and the identical strain gauge deformation at that measuring point, is proportional to the causative load [25].

This feature is used to make a qualitative statement related to crimping force. The material elongation at a defined spot on the crimping hand tool can be used as meaningful measurement value. This is possible, due to the proportionality between the applied force on the tool and the measured material elongation [25], as follows:

$$F_{Tool} \sim k \cdot \varepsilon \tag{4.2}$$

$$\varepsilon = \Delta l/l \tag{4.3}$$

F_{Tool} = applied force on the crimping tool

k = material dependent constant value

ε = material elongation

l = material length

Δl = variation in material length

4.4.1.1 Wheatstone Bridge

The conversion of the resistance-variation ΔR into voltage-variation ΔU is realised by the use of a Wheatstone measurement bridge [25]. This well-known technique is basically used for processing a strain gauge's signal, and it is composed of four impedances, which are interconnected in a closed shape. Figure 4.3 illustrates a basic Wheatstone Bridge.

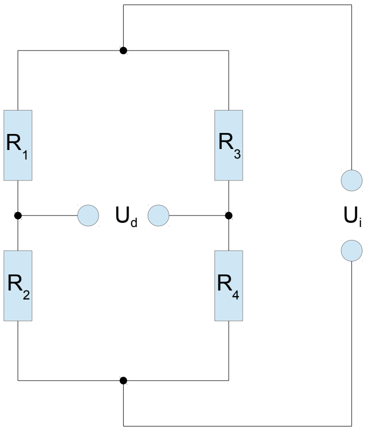


Figure 4.3: Basic Wheatstone Bridge **[25]**

Supplied by a constant input voltage U_i, the difference of the bridge voltage U_d is $U_d = 0$, as long as the bridge is symmetrical in relation to the impedances' electrical values. Thus, the electrical potential U_d, which depends on each single element in the circuit, is an indicator for the absolute electrical resistance and its variation.

The transfer function of the circuit can be stated as follows [25]:

$$\frac{U_d}{U_i} = \frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} = \frac{R_1 \cdot R_3 - R_2 \cdot R_4}{(R_1 + R_2) \cdot (R_3 + R_4)} \tag{4.4}$$

The scaled state of the bridge transition is defined as the following correlation [25]:

$$R_1 = R_2 = R_3 = R_4 \tag{4.5}$$

Thus, the bridge's potential approaches $U_d = 0$. Basically this is the most convenient state for measurement actions.

4.4.1.1.1 Wheatstone Quarter Bridge

Assuming that a strain gauge's electrical resistance replaces one of these fixed impedances, the resulting circuit is called a Wheatstone Quarter Bridge. Figure 4.4 shows the example to replace the impedance R_1.

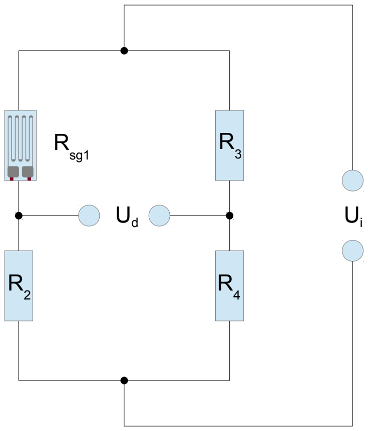


Figure 4.4: Wheatstone Quarter Bridge **[25]**

The strain gauge's variation of its electrical resistance value leads to a proportional change of the bridge voltage U_d and therefore represents a useful measurement signal in relation to the proportionality to the relative resistance change $\Delta R / R_0$ and consequently to the material elongation ε [25].

The reaction sensitivity can be assumed as follows [25]:

$$x = (quantity\ \ of\ \ strain\ \ gauges) \cdot \frac{\Delta R / R_0}{\varepsilon} \tag{4.6}$$

4.4.1.1.2 Wheatstone Half Bridge

Further, the use of two strain gauges, instead of fixed impedances, leads to a circuit, which is referred to as a Wheatstone Half Bridge.

Figure 4.5 shows a typical Wheatstone Half Bridge; by the replacement of impedance R_1 and R_2. The main condition for this arrangement to work is to have opposed elongation directions; otherwise the strain gauges need to be arranged in a transverse manner [25].

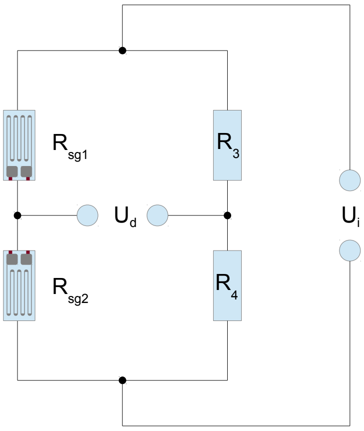


Figure 4.5: Wheatstone Half Bridge **[25]**

Subject to this stated condition, the reaction sensitivity of the Wheatstone Half Bridge can be enhanced, as compared to the Wheatstone Quarter Bridge.

4.4.1.1.3 Wheatstone Full Bridge

As a consequence, if the circuit comprises only strain gauges, and no fixed impedances at all, the arising circuit is called Wheatstone Full Bridge. Using this configuration of interconnected strain gauges, the related reaction sensitivity formula, $x = 4 \cdot \frac{\Delta R / R_0}{\varepsilon}$, can be considered [25].

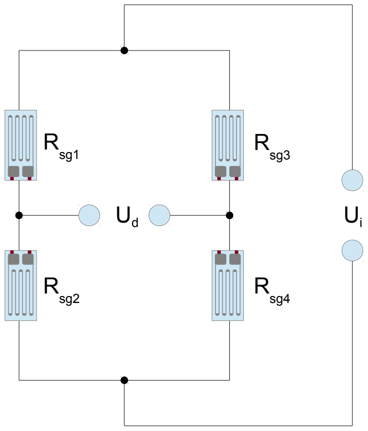


Figure 4.6: Wheatstone Full Bridge **[25]**

Figure 4.6 illustrates the optimal arrangement of strain gauges, considered as Wheatstone Full Bridge.

4.4.1.2 Strain Gauge Design for Temperature Compensation

Nowadays, a large number of different strain gauge shapes and designs are available. The majority of them are developed to withstand abnormal environmental conditions, so that they are suited to their application environments. To tolerate environmental influences, such as fluctuation in temperature, an existing design solution is suggested that is applicable to this project work. This design is shown in Figure 4.7 and it is referred to as a ‘90° displacement dual-grid’ scheme.

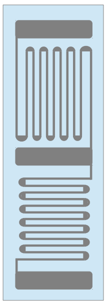


Figure 4.7: 90° displacement dual-grid strain gauge

Using the '90° displacement dual-grid' scheme, fluctuation in temperature, especially at the measuring point, have no influence on the measured electrical resistance of the strain gauge, when the conversion circuit is performed as a Wheatstone Half Bridge, which is shown in Figure 4.8.

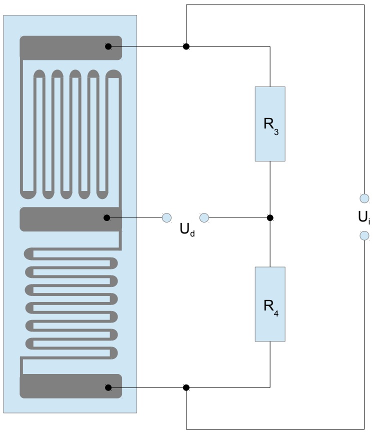


Figure 4.8: Wheatstone Half Bridge – temperature compensation layout

In this design, when the temperature in the measurement spot is rising, the electrical resistance of the strain gauge's grids is decreasing, equally, in main-elongation direction as well as in lateral direction. This means that the electrical potential, between the displaced grids, remains constant and does not cause any changes of the bridge voltage U_d.

4.4.1.3 Signal Processing

Using an Analog-to-Digital-Converter (ADC), the bridge voltage U_d can be processed. Typically, ADC components are equipped with an Inter-Integrated Circuit (I^2C) serial interface to transfer the data to the microcontroller. The basic principle is shown in Figure 4.9.

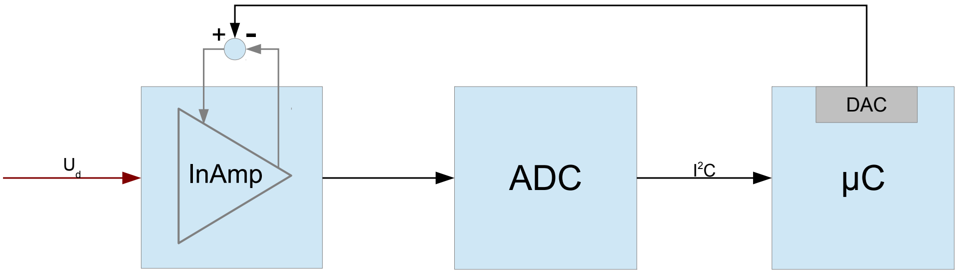


Figure 4.9: Basic force-measurement principle

The voltage difference, as the input of the instrumentation amplifier (InAmp), is amplified and transferred to the high-resolution ADC. Once the conversion is done, the data is presented to the microcontroller (µC) through of the I^2C interface.

To allow a highly-sensitive measurement, it is necessary to use the ADC's entire bit range resolution. Hence, the measurement signal should ideally not comprise any offset voltage. In real life, some offset voltage in the electronic measurement system will be present.

4.4.1.3.1 Offset Alignment

A highly sensitive measuring setup, as shown in Figure 4.8, can be influenced by a high number of disturbances, such as: material corrosion, humidity, atmospheric pressure, etc. It is crucial to consider these important and often unpredictable influences, so as to ensure the repeatedly of voltage offset, which can be significant for the resulting measurement. Therefore, this offset needs to be detected and aligned.

Considering the inoperative state, the voltage U_d is at a low offset value, which relates to miscellaneous environmental influences. Using the microcontroller's integrated DAC, an analog signal can be fed back, to compensate the offset, in a simple control-loop fashion.

Such functionality is conventional and does not need new development. Such technology exists based on a single chip, which is the 'Zooming ADC^{TM} SX8723' from Semtech Corp. [26]. As illustrated in Figure 4.10 this chip provides the key elements for processing the measurement voltage.

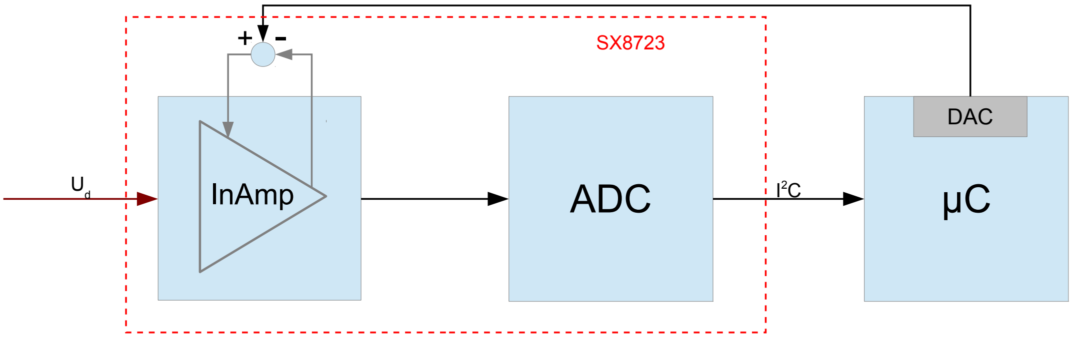


Figure 4.10: Basic principle and highlighted ZoomingADC^{TM}

The detailed schematic description of this special ADC can be found in Figure 4.11; the picture is from Semtech Corp. [26].

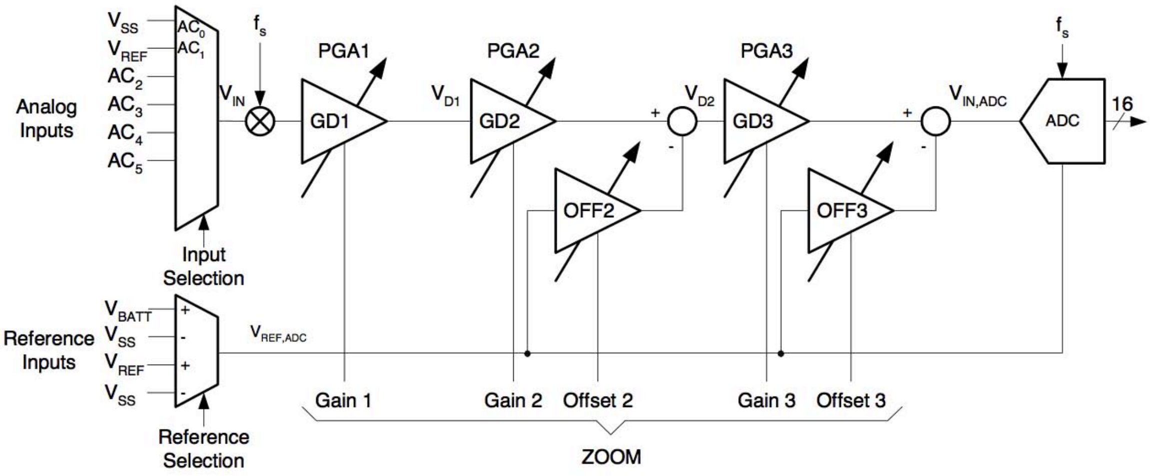


Figure 4.11 ZoomingADC^{TM} general functional block diagram **[26]**.

A visual explanation of the signal's behaviour is shown in Figure 4.12.

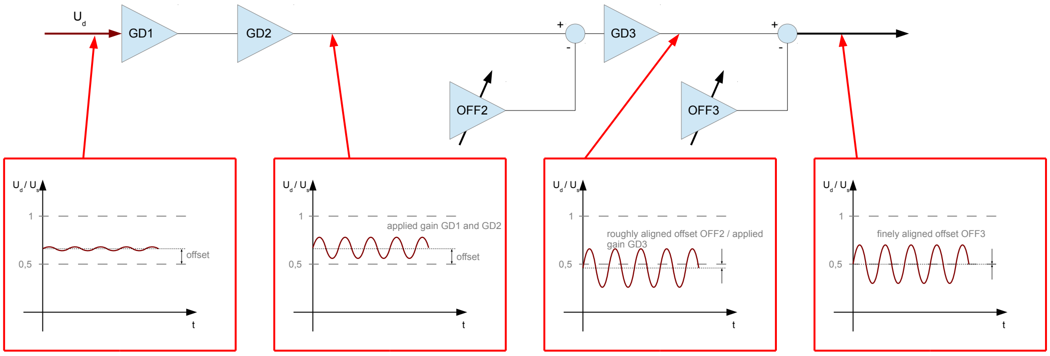


Figure 4.12: Signal processing ZoomingADC^{TM} **[26]**

When the offset of the measurement circuit is compensated, in a sufficient manner, the actual measurement process can be initiated.

4.4.2 Tool Stroke

As already stated above, due to human influences on the tool’s operation, a simple ‘force-over-time’ evaluation, alone, would not be useful. Hence, a second sensor component needs to be applied to realise a ‘force-over-distance’ consideration, which guarantees the necessary repeatability.

As there is no general solution for each individual type of crimping hand tool, various sensors for providing a non-contacting measurement, as well as a contacting measurement, are discussed below.

4.4.2.1 Non-Contacting Measurement

Inductive Distance Sensor

Figure 4.13 shows an ‘inductive distance’ sensor from Micro-Epsilon GmbH [27]**.**

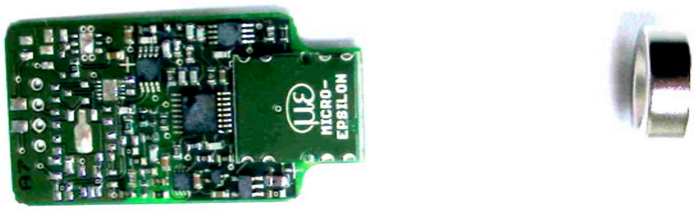


Figure 4.13: Inductive distance sensor MDS$^{\text{TM}}$ **[27]**

The MDS$^{\text{TM}}$ provides an analog output voltage in a range of 0,5V - 4,5V with a sensitivity of 0,069V/mm.

This sensor could be attached on two tool components, which are moving relative to each other. Figure 4.14 shows an example application.

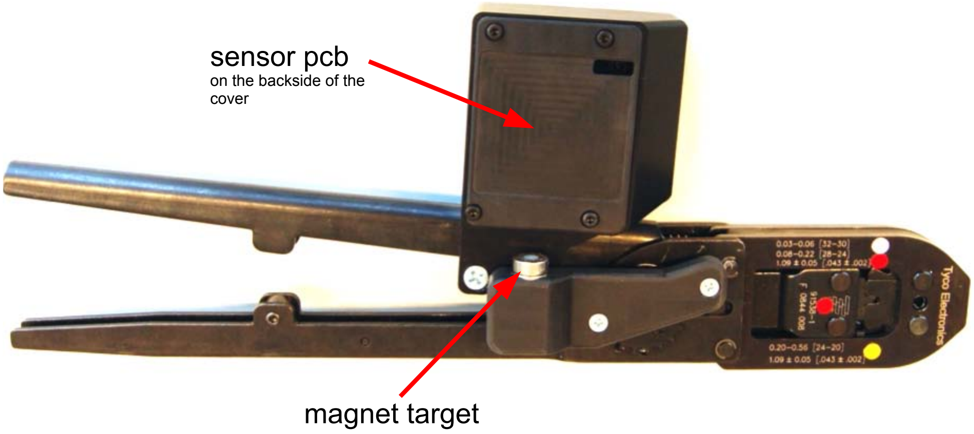


Figure 4.14: Application example for an inductive distance sensor

Magnet Angle Sensor

Figure 4.15 illustrates a magnet angle sensor from ASM GmbH [28].

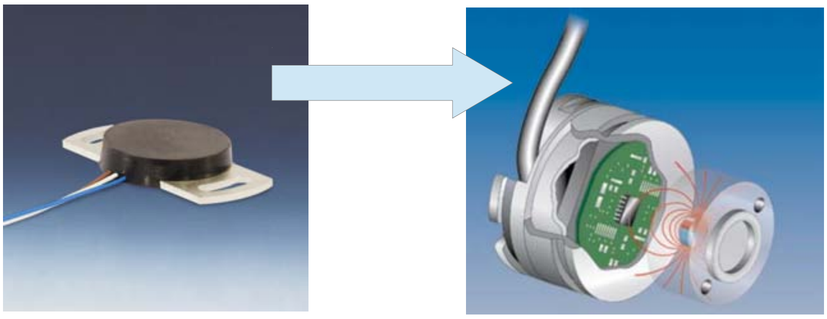


Figure 4.15: Magnet angle sensor PRAS20/21**[28]**

The PRAS21 provides an analog output and the signal ranges from 0V to 5V and can be matched on a range: minimal 15° and maximum 360° of rotation. The physical basis for sensing is the Hall effect.

If a crimp tool provides any rotary mounted parts, which are moving relatively, a sensor such as the PRAS21, could be applied. This can give a high-precision, high-resolution setup to transduce the tool's process movement.

An application example is shown in Figure 4.16.

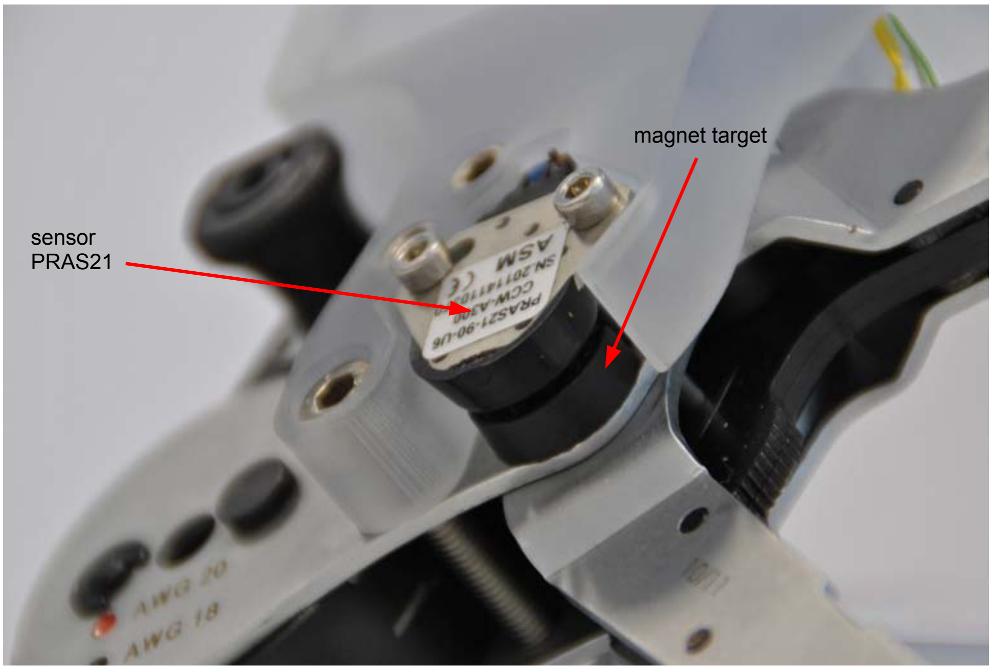


Figure 4.16: Application example PRAS21

4.4.2.2 Contacting Measurement

Rotary Potentiometer

As with the 'magnet angle' sensor, a rotary potentiometer could be integrated into the tool's mechanism, where two components are moving relative to another on a rotary basis. Due to its low cost, and a sufficient accuracy at a wide angle, it can be considered as a useful solution, for the right circumstances.

Figure 4.17 shows a rotary potentiometer from the company Altmann GmbH [29].

Figure 4.17: Rotary potentiometer T18 **[29]**

4.4.2.3 Signal Processing

Since the microcontroller has an integrated ADC, the signal can be transmitted directly to the relevant port of the microcontroller.

The voltage conversion process, using an ohmic voltage divider, and a low-pass filter at a cut-off frequency at 50 kHz, is shown in Figure 4.18.

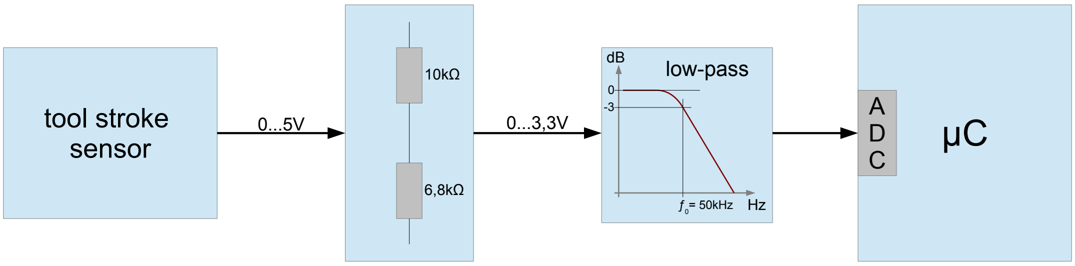


Figure 4.18: Signal processing for the tool's stroke sensor

4.4.3 Acceleration

Modern smart phones demonstrate the benefits of using acceleration sensors. Certain motion-related operation features, as well as the enhanced power management features, are possible applications for such sensors.

For this project, a digital accelerometer from Analog Devices, Inc., the ADXL345, was deemed to be the most suitable. This is a digital, low power, 3-axis-accelerometer with a resolution of 13 bits at maximum +/-16g (gravitation), and it is developed especially for portable and mobile devices, for integration into embedded systems, with the focus on energy savings [30].

Figure 4.19 shows the functional block diagram of the ADXL345. The diagram is from Analog Devices, Inc. [30].

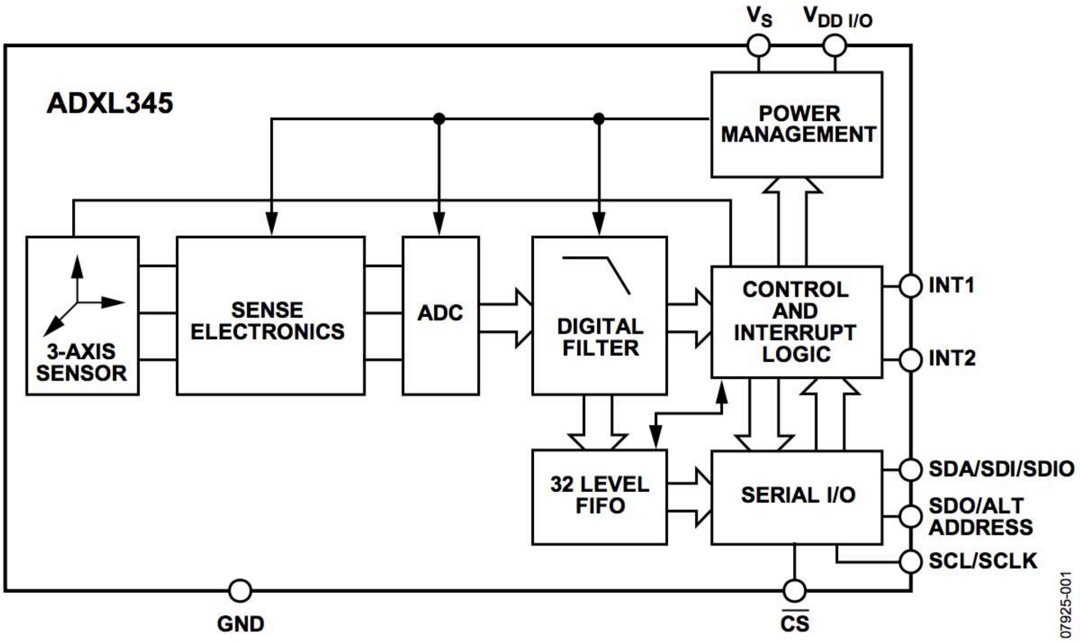


Figure 4.19: Functional block diagram ADXL345 **[30]**

The ADXL345 comprises certain useful predefined functions, such as tap or double tap detection, free-fall detection, as well as activity/inactivity monitoring.

For digital communications, the accelerometer provides both SPI and I^2C interfaces. The communication scheme supports a simple preventive, but necessary, method to avoid bus traffic errors. The fact that the same pin, which is used for initiating SPI, is also responsible for enabling I^2C communications, this can lead to potential misinterpretations in the sequence of communication, whether SPI or I^2C is used. Preventing bus traffic errors by the use of a logic gate in front of the SDI pin (Serial Data Input) is highly recommended by Analog Devices. This scheme is schematically shown in Figure 4.20, which is from Analog Devices, Inc. [30].

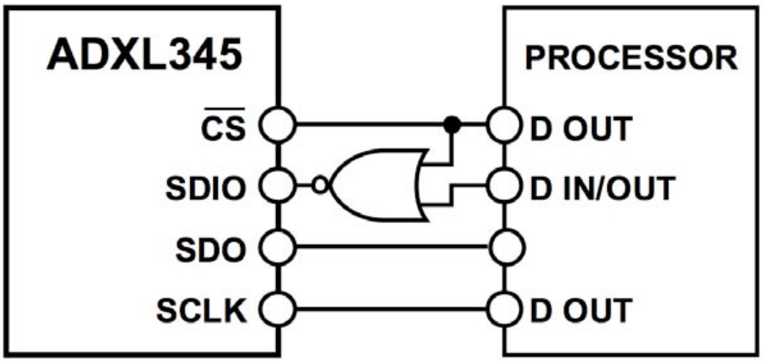


Figure 4.20: Connection diagram to prevent bus traffic errors **[30]**

4.4.3.1 Tap Detection

The tap detection mode is basically used to generate a wake-up interrupt, i.e., when the system is in sleep mode for saving energy, a quick finger tap on the tool is sufficient to trigger the interrupt routine to wakeup the entire embedded system.

Basically, a single-tap-interrupt is initiated by a single acceleration event as shown in Figure 4.21, which is taken from the datasheet of ADXL345 [30].

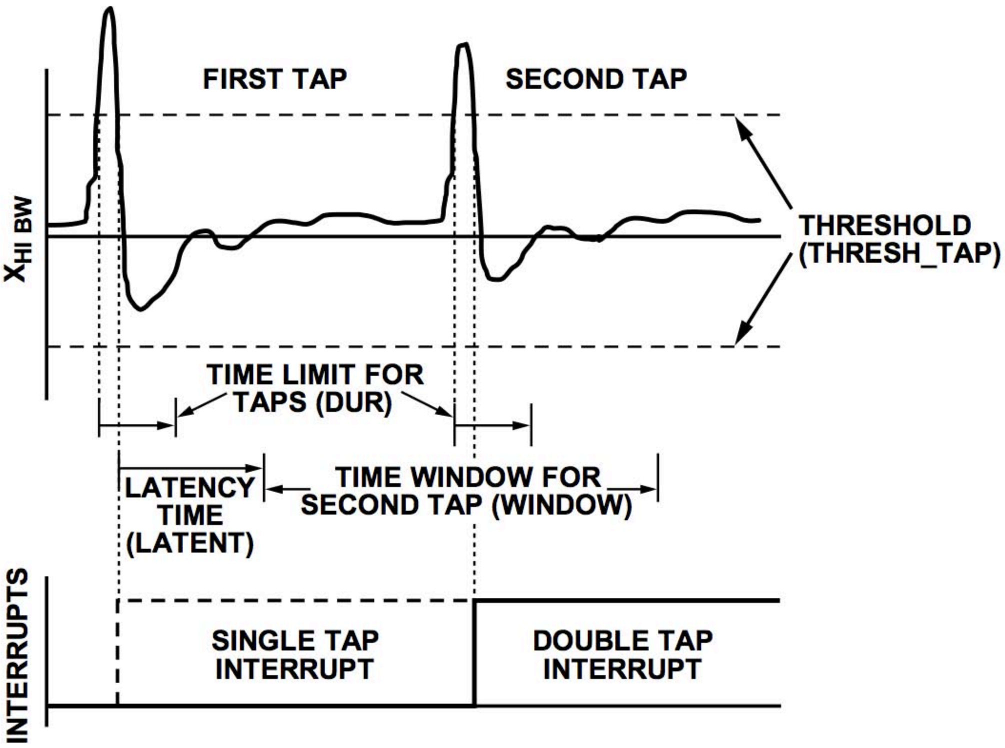


Figure 4.21: Tap interrupt function for single and double tap **[30]**

The characteristics of such a tap-interrupt can be defined by two simple parameters, time and force. The horizontal dashed threshold line in Figure 4.21 represents the force threshold, whereas the vertical lines show the time limit. Hence, if the sensitivity needs to be customized, the relevant parameters can be adjusted accordingly.

4.4.3.2 Free Fall Detection

When a highly sensitive measuring system crashes down to the shop floor, in the majority of cases it can be assumed that the system is destroyed, or its functionality is compromised in some way. Thus, any tool that is important to the production process, in quality-controlled environment, should not be trusted following such a crash. To ensure that a tool that suffers such a crash is not continued in service, the acceleration sensor ADXL345 is used to detect such a free fall; and once such a free fall is detected, the entire device can be put into a state that disables the tool, for example by blocking the display and outputting a visual or audible service signal.

A free fall interrupt is initiated when the vector sum for acceleration on all axes violates some predefined threshold value. From the instant of the start of the free fall to instant of the end of a free fall, the vector sum of acceleration at three dimensions decreases to nearly 0g (g: Newtonian constant of gravitation). The duration of this behaviour is directly related to the drop height. Hence, a way to learn the parameters for the sensor's behaviour is to experimentally research the specific use case; in a similar manner to the tap detection solution as already described.

Based on experimental experience, if the drop height is approximately 0,5m it is recommended to set the time limit at 220ms and the force threshold at 700mg (milli-Newtonian constant of gravitation).

Figure 4.22 shows the acceleration change characteristics for the case of falling at the illustrated orientation [31].

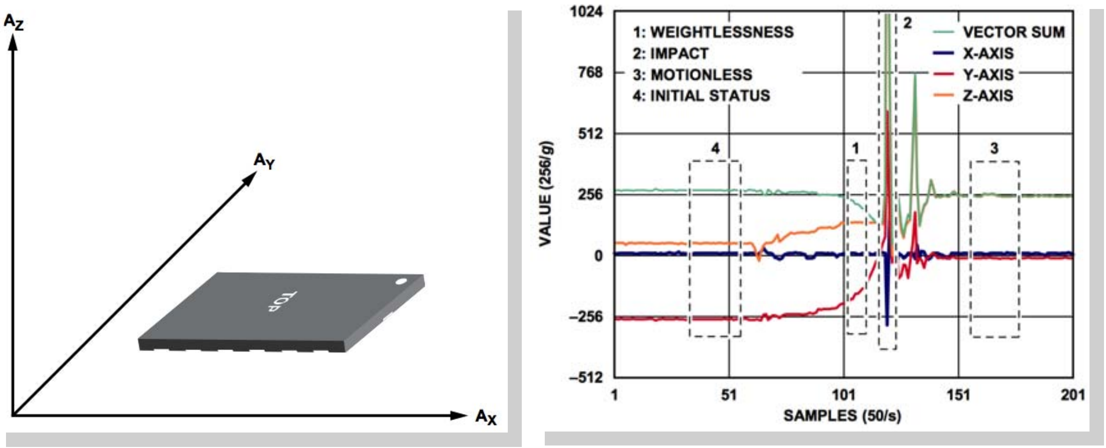


Figure 4.22: Acceleration change characteristics during free fall **[31]**

4.5 Summary

This chapter has described some of the basic sensors, and the related science and technologies, that have been explored in an effort to meet requirements for a sophisticated and stable crimp force monitoring scheme. Further, the sensing components’ signal processing schemes have been presented. The digital processing and the evaluation of the sensed signals will be described in the following chapter.

5 The Measurement Process

5.1 Introduction

The previous chapter has discussed the analog sensing requirements for a complete and sophisticated crimp force analysis (CFA) solution. The next stage in the development chain is the digital processing and evaluation of the measured raw data. The fundamental information for this activity is presented.

5.2 Objectives

This chapter explains the digital data handling approaches for the CFA with the aim to achieve a reliable, gapless measurement solution. Without post-processing of the raw data, a reliable and trustable evaluation of crimp quality cannot be guaranteed. Statistical methods are used to process the information. The full measurement procedures are described in this chapter.

5.3 Preparation of Measurement

The diagram in Figure 5.1, is built out of single measurement for a typical crimping process. This means both measurands, force and stroke, are plotted against time.

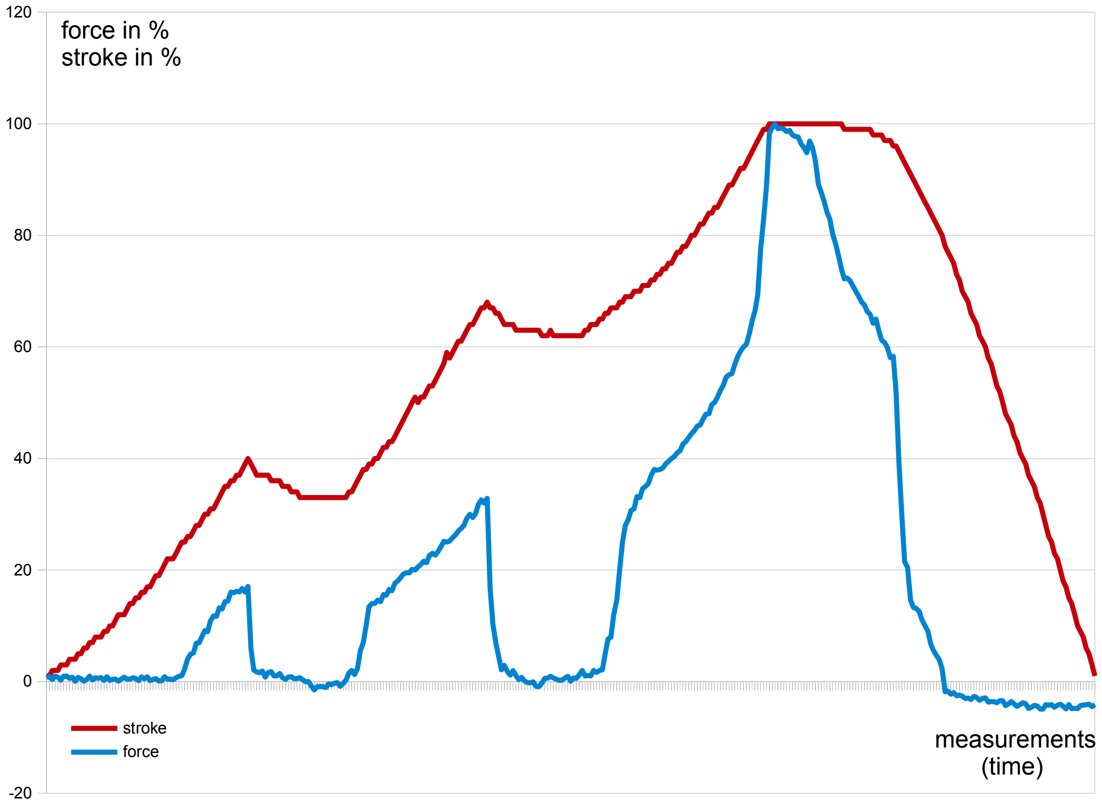
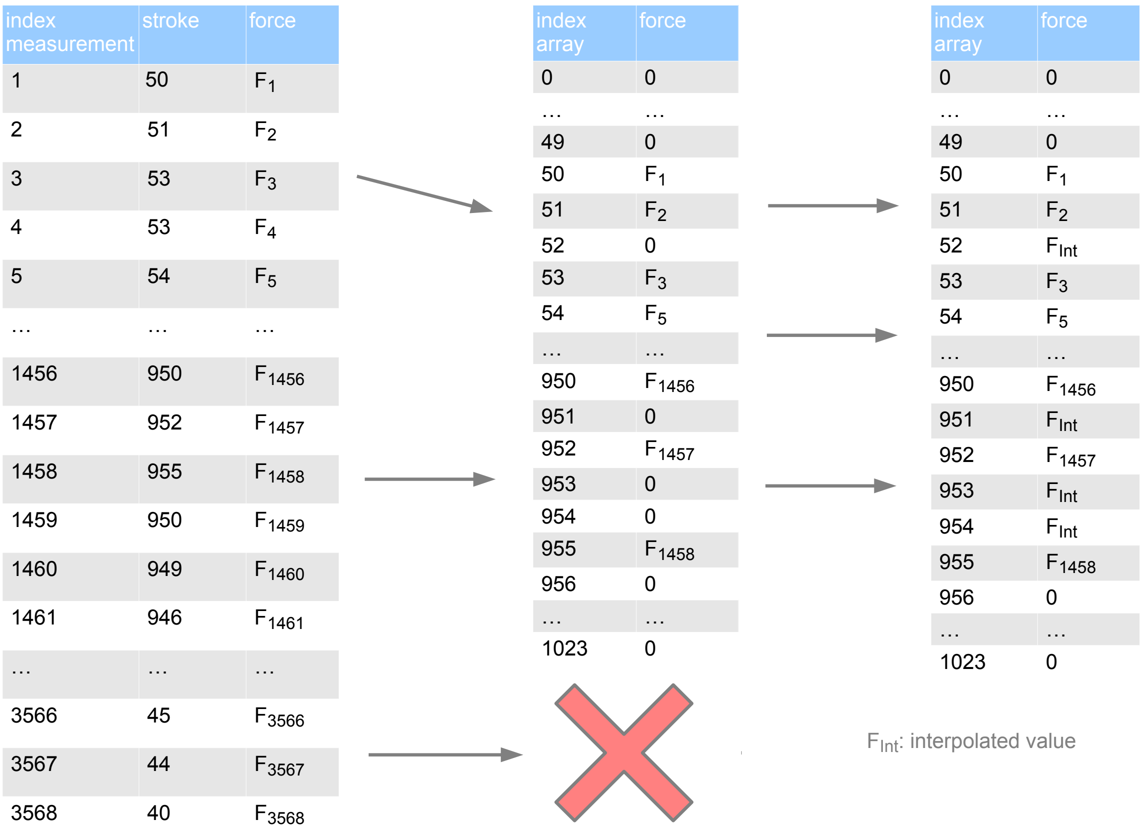


Figure 5.1: Force/stroke-over-time characteristics

Due to the human influence, crimp curves as it is shown in Figure 5.1 will never be processed in exactly the same duration over repeated crimp operations. This proposes a challenge to the development of a highly accurate crimp quality monitor. Furthermore, the amount of data that needs to be stored for an individual crimp, cannot be predicted, hence, the used storage hardware can be exhausted very fast.

As discussed earlier, this project approaches this problem by proposing a ‘force-over-distance’ evaluation for each operation of the crimp tool.

To handle these circumstances it is necessary to take out the factor time, by combining force and stroke as it is shown in Table 5.1.



index measurement	stroke	force
1	50	F_1
2	51	F_2
3	53	F_3
4	53	F_4
5	54	F_5
…	…	…
1456	950	F_{1456}
1457	952	F_{1457}
1458	955	F_{1458}
1459	950	F_{1459}
1460	949	F_{1460}
1461	946	F_{1461}
…	…	…
3566	45	F_{3566}
3567	44	F_{3567}
3568	40	F_{3568}

index array	force
0	0
…	…
49	0
50	F_1
51	F_2
52	0
53	F_3
54	F_5
…	…
950	F_{1456}
951	0
952	F_{1457}
953	0
954	0
955	F_{1458}
956	0
…	…
1023	0

index array	force
0	0
…	…
49	0
50	F_1
51	F_2
52	F_{Int}
53	F_3
54	F_5
…	…
950	F_{1456}
951	F_{Int}
952	F_{1457}
953	F_{Int}
954	F_{Int}
955	F_{1458}
956	0
…	…
1023	0

F_{Int}: interpolated value

Table 5.1: Reformatting of measurements

The measurement values are handled in real-time and are written into an array, whose index represents the stroke value. This leads to a significantly smaller memory space usage. Additionally, to further save memory, the ADC’s measured 12-bit value is reduced to 10-bit value by shifting the result bitwise to the right. In regards to the force, 16-bit integer values are used, and all this leads to a curve magnitude of a total size of 2048 Bytes. To consider the internal ADC’s (stroke) potential offset, the complete range of its resolution cannot be exploited, as the stroke values are the indices of the array. This leads to a maximal exploitation and consequently to ‘empty’ sections at the beginning and at the end of the curve. By adding two additional parameters the index of the first and the last value are given to the curve.

The graphical result of restructuring the measurements, in terms of ‘force-distance’ combination and interpolating missing values, can be found in Figure 5.2. The arrows show the chronologic progression of the crimping process. The blue line illustrates the progression on the closing of the tool, and the red line represents the progress on opening. The significant inflection point can be identified, when the tool is closed to its maximum.

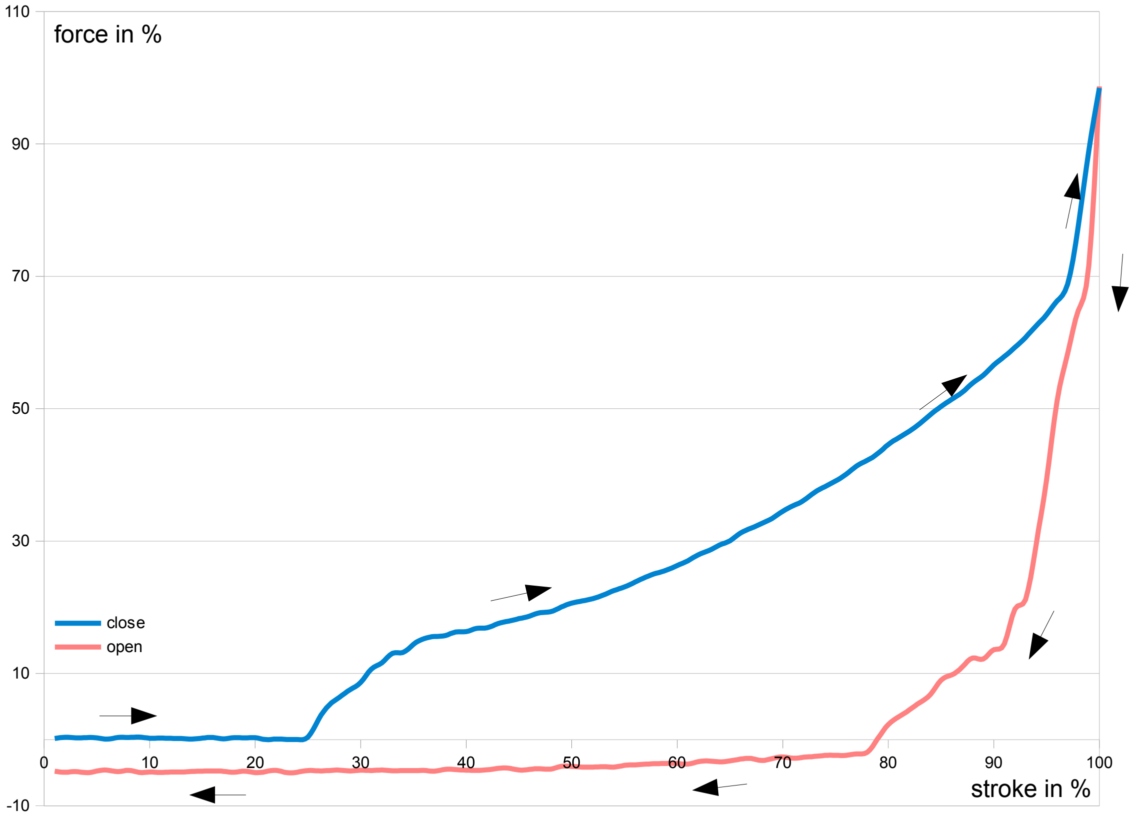


Figure 5.2: Typical measurement curve of a manual crimping process

The returning part of the graph, i.e. the red line for the closing operation, is not of relevance for the evaluation algorithm and therefore it is discarded.

An interesting and common use case is the ‘discontinue’ face of operation of the tool. This is where the operator suddenly stops driving the tool during a crimping process. Both measurands, force and stroke, are influenced. The force gets to almost zero and the stroke value declines to the previous mechanical ratchet position. The graphical outcome of this use case is shown in Figure 5.3.

However, this use case is not an issue of concern in determining a good or bad crimp connection. A perfectly good connection can be arrived at, even where such discontinuities existing during the crimp process. Such discontinuation simply implies the interruption of crimping progress at some position A, which is indicated in Figure 5.3, with two examples of discontinuation. As already stated, the tool returns open to a defined mechanical limit and influences both measured parameters: stroke as well as force. The effect of the crimping material's rebound, leads to an unexpected characteristic curve as shown in Figure 5.3. At position B the value of force returns to the same level as it was previous to the discontinuation interrupt. As such an event would be detected and evaluated, all individual measurement points, which are lying in between A and B, are simply scrapped and replaced by linear interpolation. The adjustment is indicated as light green lines in Figure 5.3. These interpolation values are not perfect ones, but their influence on the evaluation is not significant.

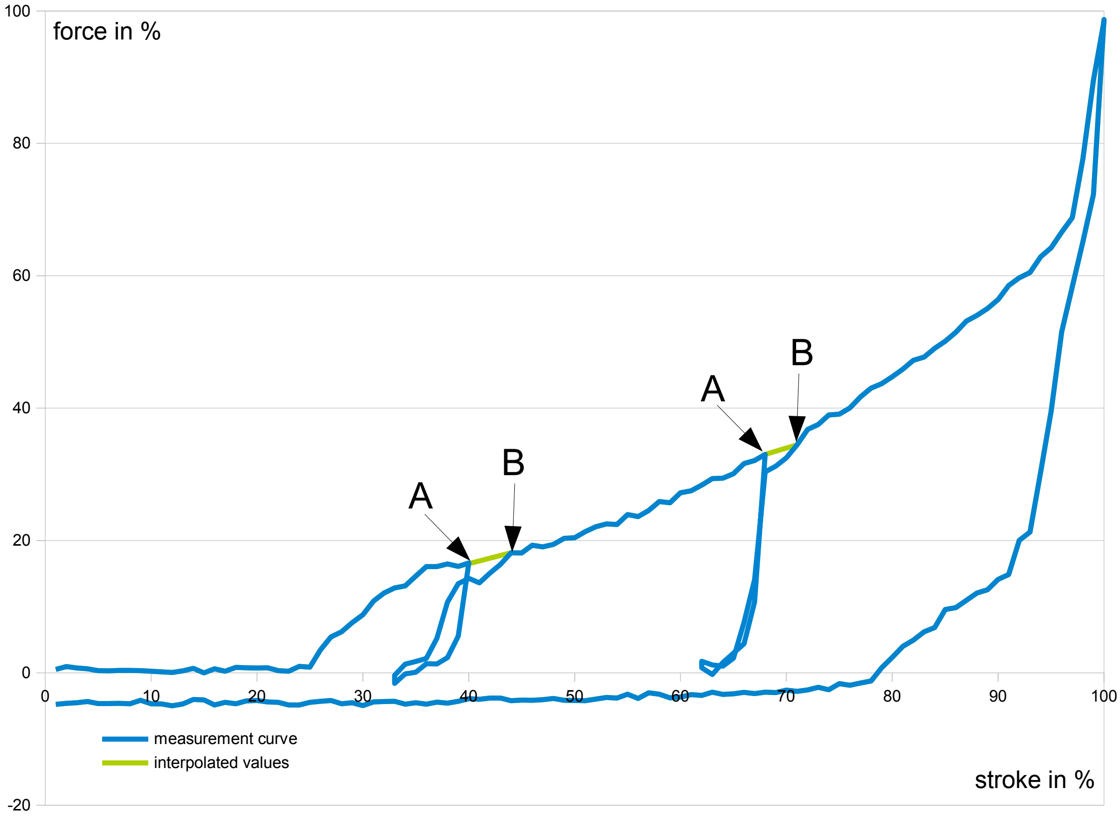


Figure 5.3: Measurement curve of a discontinuous manual crimping process

The basis for this consideration is a monotonic increasing shape of the crimp curve. But, in a real system, actual failures can cause a non-monotonous shape, as well. Hence, the challenge is to separate the two cases: 1) ‘discontinuous operation’, and 2) ‘crimping process failure’, without misguiding the rating process. So the policy is not only to compare two consecutive values in terms of monotonic character; it is also to find out how big is the gap between these compared values. This can be achieved by calculating the slope between these two measurement points.

$$m = \frac{\Delta y}{\Delta x} = f_{n-1} - f_n \tag{5.1}$$

When this slope value comes below a defined threshold, the consecutive force measurement values will be ignored. The curve’s progression will not continue until one force value rises again, and overtakes the threshold.

5.4 Post-Processing of Measurements

Commonly, the various manufacturers’ handheld crimping tool products are significantly different in their internal mechanism designs. These differences might lead to remarkable influences on the measurement signal’s behaviour. Therefore, the preparation of measurements, as described in Chapter 5.3, is sometimes not rigorous enough. In this regard, consider two possibilities, which are detailed in the following subsections: 1) smoothing and 2) offset alignment. These features are investigated can be applied if it is considered necessary in a design.

5.4.1.1.1 Smoothing

To reduce potential measurement noise, it is desirable to smooth the curve by using a ‘moving average’ policy. A ‘moving average’ policy corresponds to a low-pass filter and it is calculated based on an odd number of stroke values. Especially for this application, a filter with an order of three or five has been shown to be suitable. The order indicates the number of data points, which are used to process one average value. For example, a moving average with the order of five can be stated as follows:

$$y_i = \frac{1}{5} \sum_{k=i-2}^{i+2} y_k \tag{5.2}$$

Another possibility for smoothing a measurement curve is the ‘weighted moving average’ policy. Using this, each single data point is weighted according to a matrix structure:

$$y_i = \frac{1}{\sum k} (k_1 \cdot y_{i-2} + k_2 \cdot y_{i-1} + k_3 \cdot y_i + k_4 \cdot y_{i+1} + k_5 \cdot y_{i+2}) \tag{5.3}$$

Using an appropriate weighting matrix, such as a triangular window, the later measurement values have more influence on the result than the preceding ones; and the resulting average value is rather less distorted as compared to the un-weighted alternative policy.

5.4.1.1.2 Offset Alignment

An additional force ‘offset alignment’ feature in the post-processing sequence can be implemented. In an attempt to allow for environmental influences on the crimping tool mechanism, especially on the strain gauge, which can cause unpredictable offset drifts, post-processing for ‘offset alignment’ can be desirable.

In contrast to the analog offset alignment, as described in section 4.4.1.3.1, this further method is to: 1) calculate the area below the reference graph, and 2) to compare the calculated area of the currently recorded graph, to the reference.

The measured offset of the recorded curve is aligned repetitively, until the compared area is rather similar to the reference. This leads to a fast and precise approach to avoid offset influences on the rating policy.

5.5 Evaluation

5.5.1 Interpretation of the Measurement Curve

Once the measurement curve is recorded and all missing values were interpolated, various statements can be made.

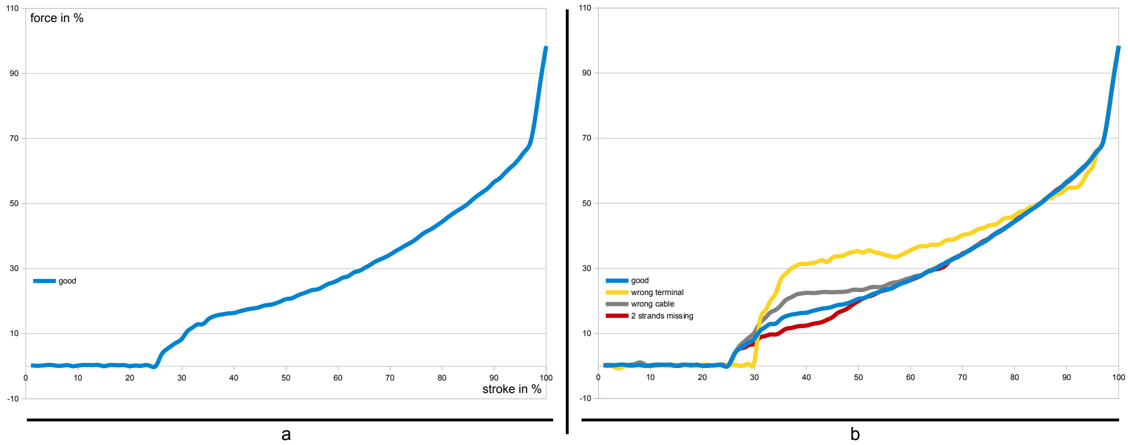


Figure 5.4: Various crimp curves

As can be seen in Figure 5.4a), at the beginning the curve takes a horizontal characteristic, due to the fact that it is still running at an idle state of the crimping tool. The moment when the actual crimping starts happen can be clearly identified, as the force values rise, at approximately 25% of the stroke for the tool’s maximum. However, when a wrong terminal is used then this position changes. A quality engineer can, later on, evaluate this behaviour, which might identify whether the correct terminal was used for crimping. The end of the curve (Figure 5.4a)) corresponds to the closed state of the tool; this pole is caused by the mechanical limitation. Thus, the end range is not well qualified to rate a crimping process on the basis of the curve’s behaviour at this position, because for this consideration, each crimping process is almost similar, whether it is good or bad.

The area, which is enclosed by the crimp curve (Figure 5.5), is a relevant criterion for evaluation. Typically, the area below the characteristic curve relates to the physical work, which was performed. Hence, using an empty crimp process sample, and a real one in comparison, it is possible to calculate the related physical work for a crimped wire termination:

$$W = \int_{\vec{r}_1}^{\vec{r}_2} \vec{F}(\vec{r}) = \int_{0\%}^{100\%} (F_{good} - F_{empty-tool}) \tag{5.4}$$

Considering Figure 5.4b), the policy of rating the physical work seems to be logical, because different crimping processes, with different conditions, can give different curve characteristics. Obviously, the determinable factor is the physical work, and hence the area below the curve.

The crimp process for the case of two missing strands requires less physical work, compared to the cable termination using an oversized cable.

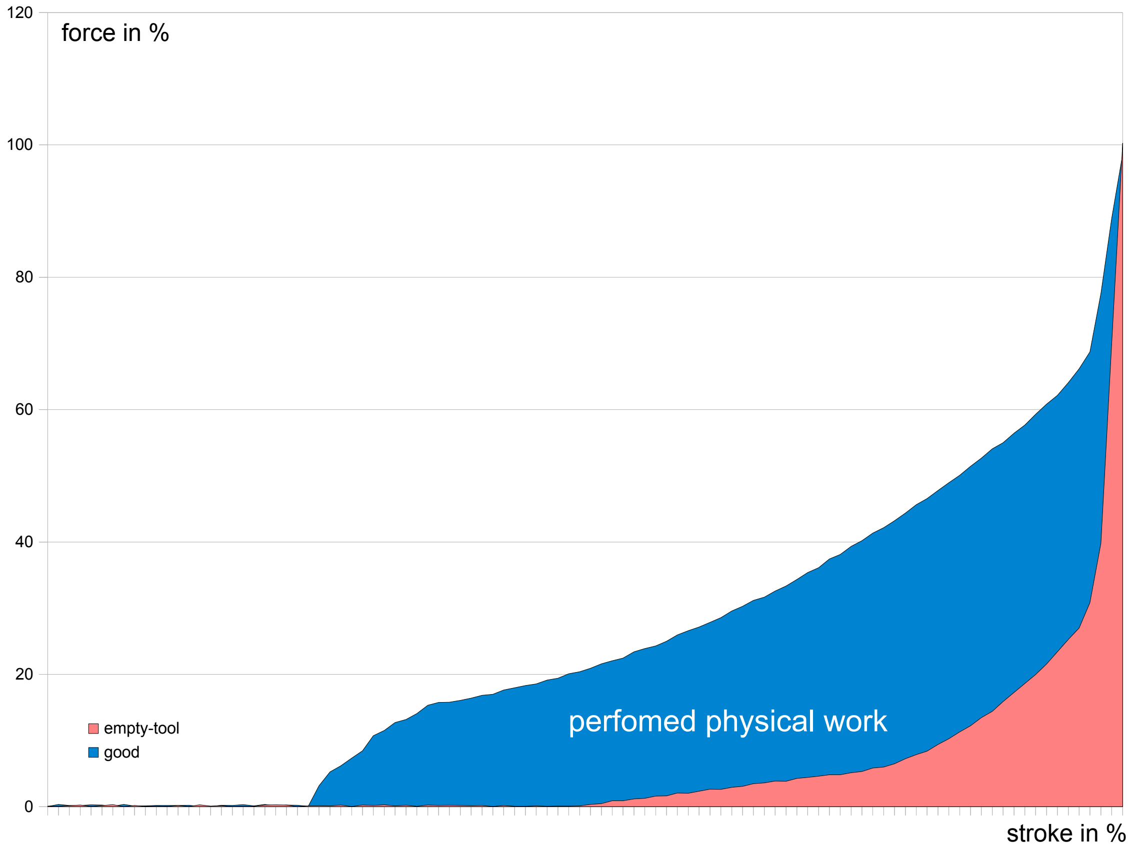


Figure 5.5: Performed physical work for a crimped wire termination

To summarise, on the basis of the measurement curves, which are shown in Figure 5.4 and Figure 5.5, it might be possible to determine:

- the beginning of a crimping process,
- the performed physical work,
- the complete curve characteristics, that considers tool position-depending behaviour.

Thus, it can be assumed that there is a specific characteristic curve progression for each single combination of tool, terminal, and cable. The fundamental aim is now, to make a quality statement by comparing these various factors, for particular tools, etc.

5.5.2 Evaluation via Normal Distribution

5.5.2.1 Generating a Reference Curve

In general, in order to make a statement on the quality of a measurement there is a need to compare results to some given agreed reference, which is built out of various specified and controlled measurements (source curves). Due to variations in the quality of materials, it is useful to use repeated measurements to avoid unwanted influences of marginal conditions. Based on the experience of measurements to date, between five and ten sample measurement sets are required to build a reliable basis for a valid reference curve.

Average-curve is built from some specific recorded control curves, whereby the arithmetic mean of force in relation to each stroke value is processed:

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{5.5}$$

For the case of a reference, which is made from a small number of curves, smoothing, as described in section 5.4.1.1.1, can be used to improve the quality of the assessment. Here, the result approaches that of a reference curve that comprises a large quantity of source curves. However, on the downside, there is a risk of negatively influencing the reference curve by the unintended involvement of any faulty measurements.

To support any credible evaluations, it is necessary to provide a tolerance band, alongside the reference curve. In addition to the arithmetic mean, the source curves can be used as well, to determine the standard deviation σ for each individual data point. This can be arranged so that 68.3% of data, which is used for calculation, would be located in between $\bar{y} \pm 1 \cdot \sigma$; 95,4% in between $\bar{y} \pm 2 \cdot \sigma$; and 99,7% in between $\bar{y} \pm 3 \cdot \sigma$. The standard deviation σ can be described as follows:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{5.6}$$

The tolerance band is applied to each significant force value resolved over a stroke. This means that there is a force tolerance range for each single stroke value. However, if one of the source curves starts late, the range to this moment will not be affected by the tolerance band. This is reasonable to assume, because at the beginning of a curve, as well as at the end, there is a quantity of insignificant measurement values.

Figure 5.6 shows a reference curve with the related tolerance band. In this particular case, the reference curve was generated from 20 sample sets and the tolerance band is based on a three times standard deviation $3 \cdot \sigma$.

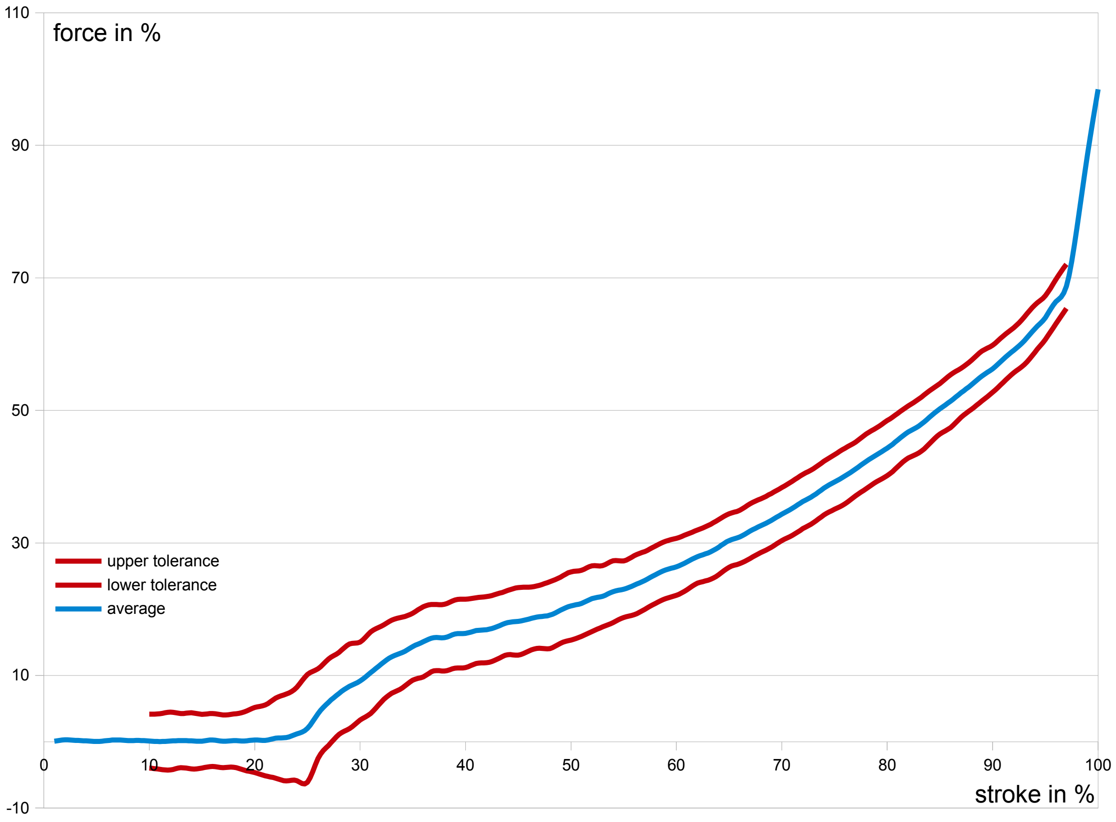


Figure 5.6: Reference curve with tolerance band as per method of normal distribution

5.5.2.2 Restrictions and Problems

There is a difficulty in the method that relates to the distribution of source curve values. In reality, not even a single crimp curve is identical to another, and consequently, there might be remarkable differences in the force value at a comparable stroke positions. There is some measurement uncertainty, temperature changes, material wear, material tolerances, etc. This problem gets minimised by using a high number of sample source curves to generate a reference curve, but the result is going to be reliable only by applying some 50, or up to 100 source curves. A high number of source curves improves the probability that unpredictable influences will not contribute negatively to the assessment. However, all this requires an excessively high effort for configuration. Just like building an average curve, smoothing can be used to tackle this difficulty. Based on the intensity of the smoothing progress this method can provide a functional solution. However, if it is done too intensively, the statistical context will be lost.

An important consideration is the result's data type. As the evaluation can be merely processed in a point-wise fashion, using the 10-bit resolution of the ADC, approximately 800 valuable data pairs are considered for rating just for one curve. A convenient method to improve on this situation would be to average over these approximately 800 single results. With this approach, failures with a very low influence on the curve, such as a low percentage with a too-low cable diameter, can be detected. However, the context to statistic standard deviation then gets lost.

5.5.3 Evaluation of Sections

An analysis of some reference curves, such as shown in Figure 5.6, leads to various perceptions and considerations. The tolerance band maintains almost the same width all along the reference curve's progression.

5.5.3.1 Analysis of the Recorded Reference Curve

In particular for well-developed reference curves, which are made out of a great number of source curves, three significant sections are highlighted along the stroke axis (x-axis). Figure 5.7 shows the partitioning of the stated reference curve.

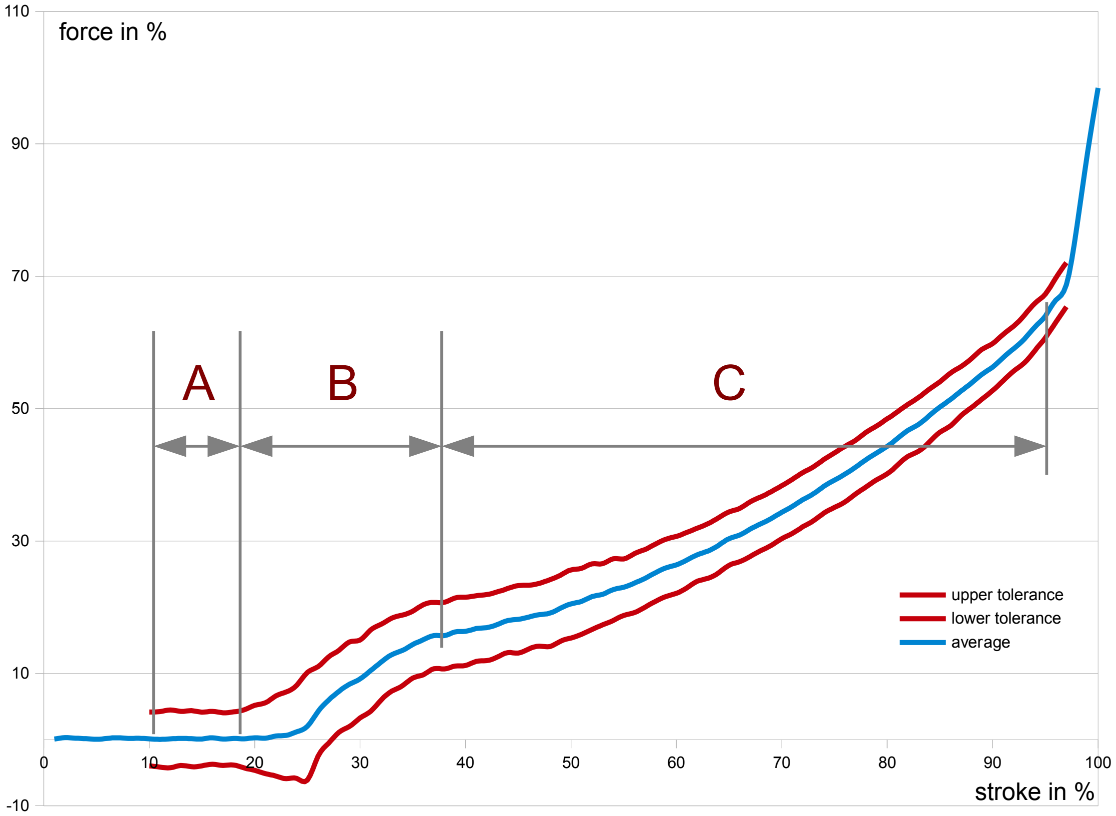


Figure 5.7: Sections of reference curve

The three sections can be described as follows:

Section A:

The beginning of the measurement cycle is rather worthless in regards to the evaluation. Typically, in this interval there is no physical touch between the tool's crimping dies and the terminal. Hence, there is no plastic deformation of material and consequently differences in this section are either caused by observational errors in measurement, or by invalid tool handling. Only very significant faults, such as the use of an oversized terminal due to earlier material deformation, affect this section.

Section B:

Section B represents a much more interesting topic. Not only does the material's deformation happen in section B, but also small failures, such as protruding strands, can cause a big impact to the curve's progression within this section. This section enables a reliable identification of all failures, which are illustrated in Figure 5.4b). The tolerance band is slightly widened; caused by different material behaviours at the beginning of initial deformation.

Section C:

In terms of evaluation, section C is rather similar to section A. The effects of a faulty crimping process are almost negligible, as compared to the effects in section B.

5.5.3.2 Method of Evaluation of Sections

As discussed, a reference curve, described in 5.5.2.1, is required, however, now we will consider the exclusion of the tolerance band. This exclusion saves on memory space, leading to half of its previous size.

For the next step, the considered curve is compared to the average curve for each section and for each individual data point. Subsequently, the average deviation for each section can be determined.

Based on the fact that each section has its own significance, they are combined with different allocated weightings. However, this weighting simply depends on the crimp termination itself, as well as on the type of tooling. For the following example the weight is about 60% at section B; 30% at section C; and 10% at section A. Consequently, it is possible to derive a quality factor *k*, as follows:

$$k = \frac{1}{a_n - a_0} \sum_{i=a_0}^{a_n} \left| y_i - \bar{y}_i \right| + \frac{6}{b_n - b_0} \sum_{i=b_0}^{b_n} \left| y_i - \bar{y}_i \right| + \frac{3}{c_n - c_0} \sum_{i=c_0}^{c_n} \left| y_i - \bar{y}_i \right| \qquad (5.7)$$

The higher the factor's value, the higher the difference of the considered crimp curve compared to the reference curve. Therefore, the higher the factor's value, the lesser is the quality of the crimped wire connection. Using adequate limits allows the making of a statement in regards to the quality of the entire crimped cable termination.

5.6 Summary

This chapter has described how the preparation and evaluation of the measurement data was achieved. The main aim was to exclude the unpredictable human influence of the human operator on the assessment rating of the process. This was achieved by applying statistical and analytical policies.

6 Development of the Tool as a Full Instrument Device

6.1 Introduction

Various approaches and methods for determining whether a crimping process is done correctly or not were discussed in previous chapters. Further, some analytic schemes and policies were investigated to characterise the distinguishing features of a crimped joint, in an effort to realise a good crimp force monitoring scheme based on using hand tools. To process the various signals and to process the statistical algorithms in real time, the hand tool will require some intelligence hardware in the form of an embedded computer. Such an embedded system is described in this chapter.

6.2 Objectives

It is important to define the hardware requirements of the microcomputer that will be able to support all of the required features for the proposed product. Then a detailed and comprehensive selection process for the embedded microcontroller needs to be carried out. The definition and specification of the required I/O interfaces needs to be established. Further, the defined requirements of the printed circuit board need to be considered.

6.3 General

Prior to any discussion on the detailed investigation work, an overview of the required embedded system’s structure is presented. In particular, the microcontroller system that was realised in an early prototype design is shown in Figure 6.1.

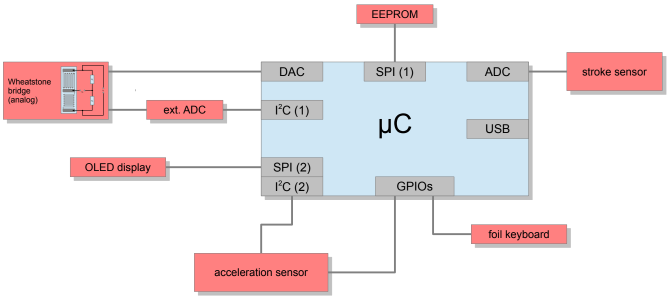


Figure 6.1: Structure of the microcontroller system

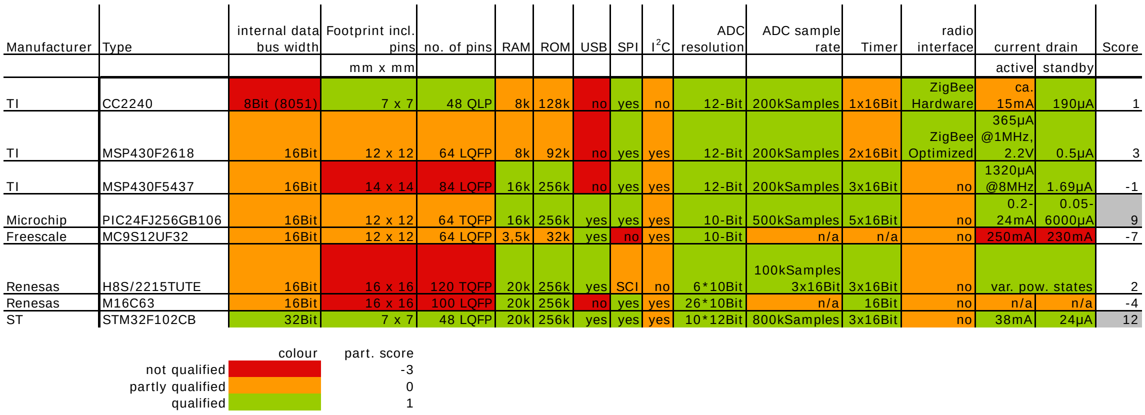
As shown in Figure 6.1 the embedded system needs to comprise various serial interfaces, as well as some general inputs and outputs. The external ADC for converting the strain gauge signal interacts with the microcomputer using I^{2}C, and the integrated DAC is used for offset alignment of the strain gauge. Some of the other blocks are self explanatory at the block diagram level.

6.4 Selection of the Microcontroller

In this research project, the proposed product device relies heavily on a core microcontroller to implement much of the functionality and features. Special emphasis is put on the communication interfaces, such as the simple serial interfaces and the Universal Serial Bus (USB). In addition to this, the memory requirements are very important. The sizes of the Random Access Memory (RAM) and Read Only Memory (ROM) modules are important as this relates to cost and functionality considerations. Optional considerations include interfaces such as radio transmission interfaces. For example a wireless network of hand tools could be achieved using ZigBee.

To achieve a good energy-saving and space-saving design, the footprint area and the current consumption were considered to be important design features.

Table 6.1 shows a list of some relevant candidate microcontrollers, including the ratings with regards to some of the above-mentioned characteristics.



Manufacturer	Type	internal data bus width	Footprint incl. pins	no. of pins	RAM	ROM	USB	SPI	I^2C	ADC resolution	ADC sample rate	Timer	radio interface	current drain		Score
			mm x mm											active	standby	
TI	CC2240	8Bit (8051)	7 x 7	48 QLP	8k	128k	no	yes	no	12-Bit	200kSamples	1x16Bit	ZigBee Hardware	ca. 15mA	190µA	1
TI	MSP430F2618	16Bit	12 x 12	64 LQFP	8k	92k	no	yes	yes	12-Bit	200kSamples	2x16Bit	ZigBee Optimized	365µA @1MHz, 2.2V	0.5µA	3
TI	MSP430F5437	16Bit	14 x 14	84 LQFP	16k	256k	no	yes	yes	12-Bit	200kSamples	3x16Bit	no	1320µA @8MHz	1.69µA	-1
Microchip	PIC24FJ256GB106	16Bit	12 x 12	64 TQFP	16k	256k	yes	yes	yes	10-Bit	500kSamples	5x16Bit	no	0.2-24mA	0.05-6000µA	9
Freescale	MC9S12UF32	16Bit	12 x 12	64 LQFP	3,5k	32k	yes	no	yes	10-Bit	n/a	n/a	no	250mA	230mA	-7
Renesas	H8S/2215TUTE	16Bit	16 x 16	120 TQFP	20k	256k	yes	SCI	no	6*10Bit	100kSamples 3x16Bit	3x16Bit	no	var. pow. states		2
Renesas	M16C63	16Bit	16 x 16	100 LQFP	20k	256k	no	yes	yes	26*10Bit	n/a	16Bit	no	n/a	n/a	-4
ST	STM32F102CB	32Bit	7 x 7	48 LQFP	20k	256k	yes	yes	yes	10*12Bit	800kSamples	3x16Bit	no	38mA	24µA	12

	colour	part. score
not qualified	🟥	-3
partly qualified	🟧	0
qualified	🟩	1

Table 6.1: Microcontroller decision table

Table 6.1 highlights two out of eight µCs, which significantly stand out within the score range of nine and twelve, based on the colour-scoring criteria stated below the table. The microchip PIC24F256GB106 and microchip STM32F102CB from STMicroelectronics were selected for further consideration. An interim decision was made to use the PIC24F256GB106 because this microcontroller has been established in market for a long time, and thus from a product sourcing point of view, it is anticipated that this part will be available for many years to come.

This PIC24F256GB106 was used in the early experimental stages for the prototype development. In the context of this research project, the first year of development was used to define the required functionalities of the product in relation to the microcontroller. The PIC24F256GB106 was capable of supporting the early-defined feature set.

However, beyond the first year, more and more features were considered to be important, as time progressed, and eventually the number of required features made it unrealistic for the PIC24F256GB106 to handle, in terms of its computational performance and the peripheral interfaces. Thus, there was a new demand to find an enhanced microcontroller to meet the additional requirements. The new microcontroller selected was the LPC1758 from NXP, which is based on an ARM Cortex-M3 32-bit microcontroller, which provides a clock frequency of 100MHz, and supports memory capacity of 64kB RAM and 512kB ROM [32].

Figure 6.2 is from the website of the company NXP Semiconductors and shows a LPC17-series microcontroller [33].

Figure 6.2: NXP LPC17xx 32-bit ARM Cortex-M3 microcontroller **[33]**

This microcontroller comprises an internal 12-bit Analog-to-Digital-Converter (ADC) and each serial bus system, SPI and I^2C, is provided twice [32]. For example, in the context of this project, using the 12-bit ADC, the resolution of the tool stroke can be increased from 10-bit to 12-bit, as compared with the PIC24F256GB106.

6.4.1 Microcontroller System

The structure of the µC system for this project is shown in Figure 6.3. In addition to the components, which are mentioned in the previous sections, Figure 6.3 also shows the communication to an Organic Light Emitting Diode (OLED) display, a foil keyboard, and an Electrically Erasable Programmable Read-Only Memory (EEPROM).

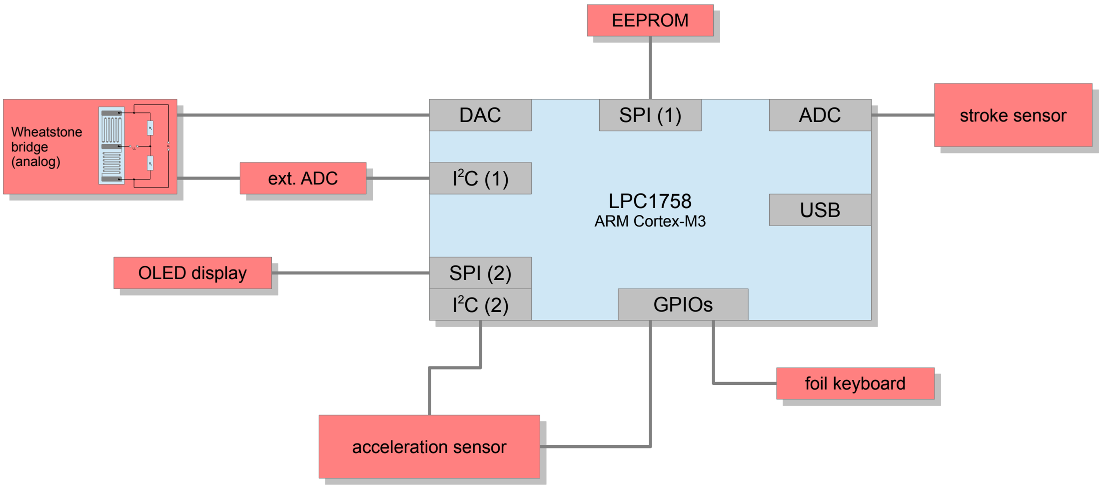


Figure 6.3: µC system structure for a new CQM scheme

Analog-to-Digital-Converter (ADC)

As mentioned above, the LPC1758 comprises a 12-bit ADC, which is used to digitise the analog input signal of the tool's stroke sensor. The resolution is sufficient to evaluate this distance measurement.

However, to handle the force signal, which is provided by the Wheatstone Bridge (Figure 6.3), the internal 12-bit ADC's resolution is not sufficient to characterise the highly sensitive strain gauge signal. Thus, an additional external ADC, which provides 16-bit resolution, is adequate for that purpose. The connection to the microcontroller is done using the I^{2}C bus.

Digital-to-Analog-Converter (DAC)

A Digital-to-Analog-Converter converts a digital value into an analog output voltage. The integrated DAC in the LPC1758 is used to arrange the necessary offset scaling at the Wheatstone Bridge, with the help of an operational amplifier circuit.

Electrically Erasable Programmable Read-Only Memory (EEPROM)

In this project the EEPROM is used to store the relevant data in a non-volatile way. In comparison to a flash memory device, the EEPROM is able to take ten times more writing cycles, without implementing lifetime extending algorithms.

Real-Time Clock

A real-time clock is used to provide the time source to support the data measurement. An additional oscillator, which provides the required frequency, is used. The real-time clock is fully functional, as long as the system stays powered up, however, once the power supply voltage drops, the clock can be synchronised simply by connection to a PC workstation.

Serial Peripheral Interface (SPI)

The Serial Peripheral Interface is used to communicate with the external EEPROM. Additionally, the microcontroller is able to interact with an Organic Light Emitting Diode (OLED), by the use of this serial communication interface.

Inter-Integrated Circuit (I^2C)

The I^2C bus is used to interface to the above mentioned external ADC, which processes the force signal.

6.4.1.1 Real-Time Operating System (RTOS)

A real-time operating system, such as the Keil RTX Real Time OS, is characterised by its small code size and by its deterministic time response, i.e. the time that is used to execute a task must be exactly determinable. Hence, a real-time operating system seems perfectly suitable to be implemented in a measuring microcontroller system, which requires precise timing behaviour.

6.4.1.1.1 Tasks

Using a RTOS the program code can be fragmented into several single tasks. These tasks are independent and self-contained processes, whose processing schedule is defined by the operating system itself. Different scheduling policies can be selected. The RTOS also supports multi-threading with thread-safe operation.

6.4.1.1.2 Mailbox

Mailboxes are used to organise the communicative interactions between individual tasks. They are used as a thread-safe First-In-First-Out (FIFO) memory to transmit data from one task to the other.

6.4.1.1.3 Semaphore

Semaphores are available and are used to synchronise multiple tasks in a conventional sense. Mutexes are implemented in the form of binary semaphore [34].

6.4.1.2 Bootloader

An additional target is to implement a bootloader to support updating the µC firmware using the USB interface. This provides a simple update procedure without any physical device disassembly.

The LPC1758 includes a primary bootloader, which is able to flash the ROM, using the serial interface. However, the embedded system in total does not provide a serial interface, hence, it is necessary to use a secondary bootloader, which supports the updating of the firmware via all available interfaces.

Based on the demonstration application, as published in the application note AN10866 provided by NXP Semiconductors [35], the secondary bootloader is located in the first two sectors of the flash memory and is executed while the system is booting. As a consequence, the flash memory capacity for the program is reduced from 512kB to 504kB.

Figure 6.4 illustrates the boot procedure and its sequence.

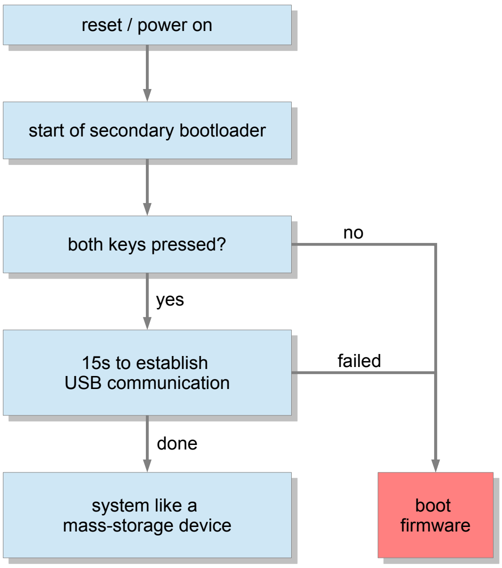


Figure 6.4: Boot up flow chart

If two predefined buttons on the keyboard are held down while the system is booting, the USB communication to a PC workstation should be established within 15 seconds. Consequently, the system can be used as a mass-storage flash device to replace the old binary firmware file with the update version. Once the system is rebooted, the new firmware is executed.

6.4.1.3 Data System of the EEPROM

To store configuration data or measurement data on the EEPROM, it is possible to use an assigned part of the storage area. This allows the development of an easy application to store a defined maximum number of reference curves. A disadvantage is that fixed storage space might give rise to some wasted space if the number of reference curves is much less than the maximum number of reference curves.

This problem can be avoided using the File-Allocation-Table16 (FAT16) file system, from Microsoft Corporation, to organise the storage area. Using this FAT16 data system, the memory capacity reduces by about ten percent, due to overhead, but the advantage is that the memory can be used in a much more flexible manner.

Figure 6.5 compares the scheme of a fixed arrangement for the storage area to the FAT file system scheme.

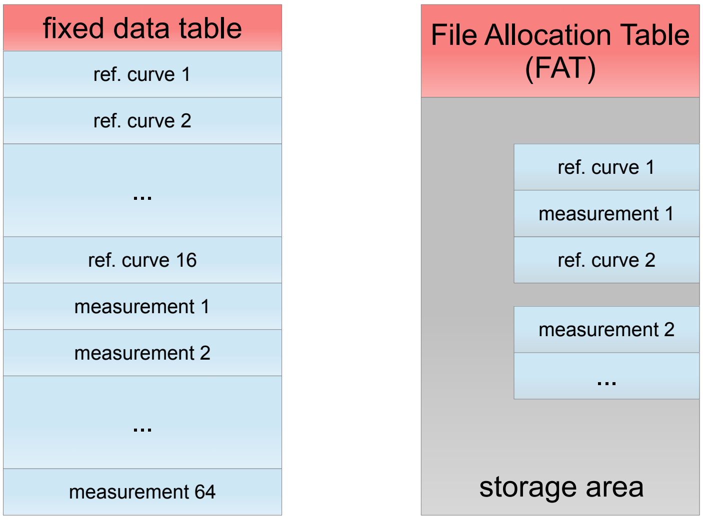


Figure 6.5: Comparison of data systems

To accommodate and implement the Flash memory file system, which is available from Keil GmbH, into the EEPROM, the organisation of the storage area needs to be worked out in the context of the C programming language. There are related issues to this configuration, where subsequent to the configuration, the SPI communication needs to be adapted into the memory model.

6.4.1.4 Firmware

The programs of the firmware code are separated into individual entities to keep the organisation simple and straightforward. With the exception of the communication interfaces, the separate tasks are totally independent from each other. As a result, the code is clear and it is easier to debug.

6.4.1.4.1 Data Recording and Evaluation

A hardware timer is used to control the recording of data, where a software timer is not sufficiently precise. A given temporal interval is predefined in the microcontrollers configuration file, and pairs of measurement values are read in frequently. This interval is crucial in terms of triggering the internal ADC as well as triggering an I^2C command to read the external ADC. Both values are transmitted via a mailbox to the ‘data recording and evaluating’ task, as soon they are received.

Figure 6.6 illustrates the task structure of the microcontroller firmware, including the RTOS components, such as mailboxes and semaphores.

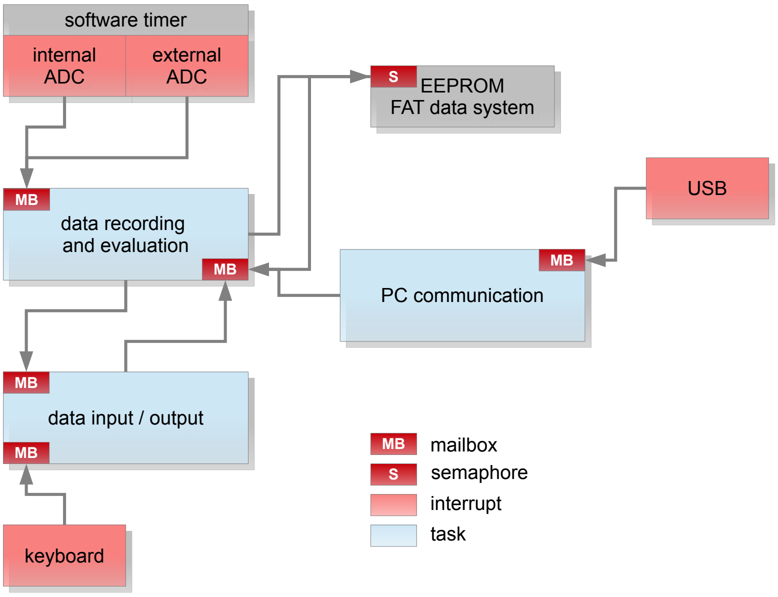


Figure 6.6: microcontroller firmware structure

The ‘data recording and evaluating’ task recognises the beginning and the end of a measurement sequence; simply by the use of two predefined threshold values, which are provided by the internal ADC (stroke sensor circuit). The task forms and evaluates the pair of measurement values as described in the previous chapter.

6.4.1.4.2 PC Communication

The 64 Byte packages received from the USB are dumped in the task’s mailbox, as illustrated in Figure 6.6. Subsequently, the task will handle those packages, as the relevant protocol defines.

For example, when a control command is received, such as a command to read the external ADC, the relevant command is given to the mailbox of the ‘data recording and evaluation’ task. Hence, a data package that includes the current measurement data is returned by using the same mailbox structure.

An additional and very important function of this operation is to save the configuration files and the reference data to the EEPROM. Figure 6.6 illustrates this situation.

6.4.1.4.3 Data Input/Output

To handle the data, beyond the USB communication, requires the GPIO interface, and an additional task is used to take care of the incoming keyboard interrupts and to take care of the output for the information to the display.

6.4.2 Data Acquisition

As described in section 6.4.1.4.1 the ADC is read out continuously, as long as the µC is not in sleep mode. Once the crimping tool specific stroke threshold is exceeded, the measurement is started. The transduction of the force, as well as the stroke signal, is done at a frequency between 50Hz and 250Hz.

6.4.2.1 Digital Filtering

Digital Filters are used to exclude undesirable noise from the entire data acquisition process. A combined filter with a minimum number of coefficients is implemented with the aim of saving computing power within the microcontroller.

The detailed investigation and the related filter design can be found in SLE's Technical Documentation: 'A combined method for enabling precision force measurement with strain gauges in a mobile system' [36].

6.5 Printed Circuit Board (PCB) Layout

6.5.1 Requirements

To meet the requirements of a mobile crimp force monitoring system, the PCB layout needs to be easily integrated into a small geometry without loss of any functionality. The complexity and the number of layers grows relative to the geometric dimension reductions.

The main requirements for the product in the context of the PCB are as follows:

- The geometric dimensions are related to the battery's size
- Maximum layer quantity is four, as cost increases significantly beyond this.

Some additional considerations are necessary.

6.5.2 Preliminary Considerations

The geometric requirements are very important for the PCB's layout. A key issue is the assumption of a very small CFM system, so as to realise a user-friendly and ergonomic crimping tooling. It is important to note the fact that the operational power supply unit will be a battery, which is located in the same housing as the PCB. Thus, the dimensions of that battery will be a consideration in defining the PCB's dimensions.

The switched electrical power supply potentially causes electrical disturbances at MHz frequency range. Therefore, it is important not to place the microcontroller in immediate proximity to the power supply. As a consequence, an internal PCB layer is exclusively used as the supply layer for all digital signals. A second internal layer is used to merge all electrical grounds in a star pattern. Based on the insulation between the two inner layers, an inherent capacitor is realised; allowing further disturbances on the supply layer to be dampened.

Using vias, the various layers are interconnected. However, it is important to ensure the optimal quantity of vias are used with the correct positioning.

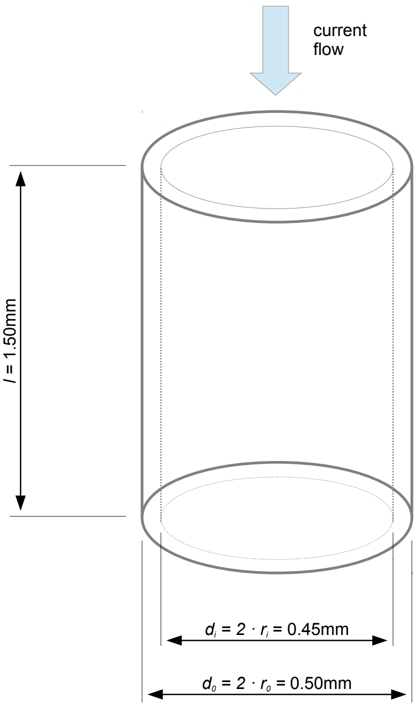


Figure 6.7: Via – layer interconnection

The electrical resistance of an interlayer connection can be determined using the following formula.

$$R_{via} = \frac{\rho \cdot l}{\pi \cdot (r_0^2 - r_i^2)} \tag{6.1}$$

For the illustrated via (copper) in Figure 6.7, the following can be stated:

$$R_{via} = \frac{0.0178 m\Omega \cdot mm \cdot 1.50 mm}{\pi \cdot (0.25^2 - 0.225^2) mm^2} = 0.72 m\Omega \qquad (6.2)$$

Therefore, a significant voltage drop across a via is possible, at high currents. This may leads to internal disturbances in regards to output voltage control. Hence, the electrical resistance of a control's feedback towards a load needs to be minimised.

The microcontroller system contains various stabilisation outputs, which are used for ADC and DAC. These outputs are wired up with filters.

The positioning of the circuit cluster can be finalised as shown in Figure 6.8.

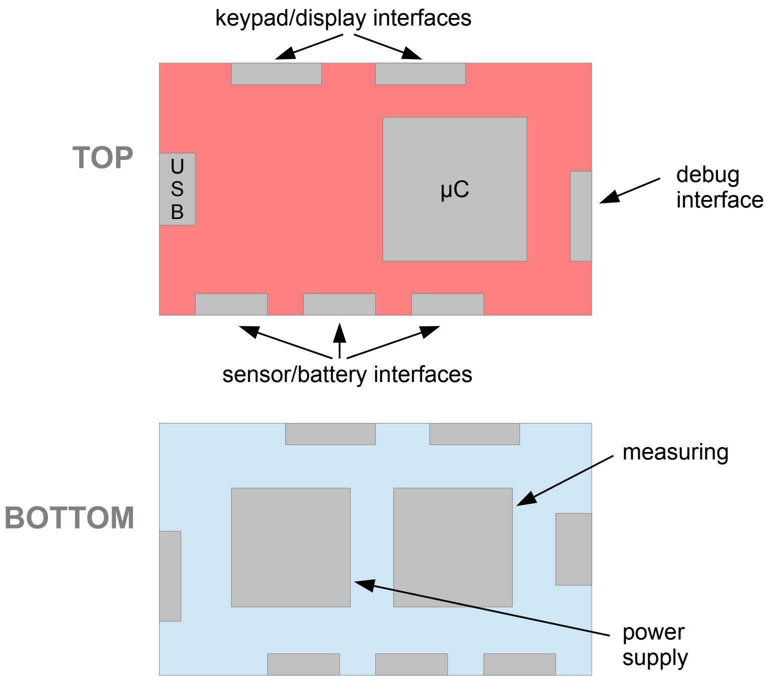


Figure 6.8: PCB component placement

Routing

The general requirements in relation to routing are as follows:

- Electrical power supply - create best possible large areas for current load paths
- Measurement path must be as short as possible

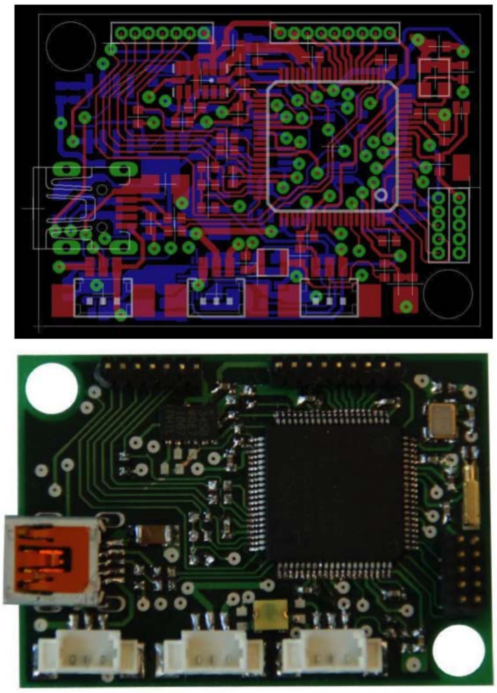


Figure 6.9: Routed PCB; finished component mounting

6.6 Summary

This chapter describes the CFA’s central processing unit. The selection of the microcontroller and its features are described, not exhaustively, but in sufficient detail. Furthermore, the functionality of the implemented operating system and the FAT16 file system were shown in some detail. Subsequently, the structure of the firmware was described. Finally, the design of the printed circuit board was shown.

The following chapter discusses the prototype configuration and validation for the proposed CFM system.

7 Prototype Construction, Evaluation, Validation and Testing

7.1 Introduction

Before a new crimp force monitoring scheme, CFM, can be introduced into the market place, it is necessary to validate and test various technical and performance related features. In this project, such a CFM solution will be embodied as an embedded hardware device that attaches to an existing manual crimping tool. Since there is a high diversity in the types of manual crimping tools that are available in the current market place, it becomes difficult to globally qualify the prototype CFM solution. The approach, within the scope of this research project, will be to target some specific hand tools as candidates for early assessment. In the initial trial the CFM solution is assessed by retrofitting the CFM solution to one type of hand crimping tool, as will be described in this chapter.

7.2 Objectives

The key objective of this chapter is to evaluate the proposed CFM scheme in the context of real tool integration. There are many aspects to consider. In some sense it is more of a challenge to develop a retrofit solution to a production device, rather than to develop a full tool solution from scratch. However, this project is proposing the retrofit approach for reasons that have been discussed earlier on. In order to provide a comprehensive treatment of the assessment, the description needs to address many factors including the development of an appropriate product physical enclosure. The implication of electromagnetic and climatic extremes is also very important and for this relevant measurements are investigated and reported upon.

Experimental mechanical testing setups are established so as to help generating repeatable and comparable tool operations, which might be as close to the real operational practices as practicable.

7.3 The Proof of Concept System

7.3.1 The Tool

As already sated above, the variety of hand crimping tools from suppliers in the market place is far too wide to allow this project to suggest a comprehensive crimp force monitoring scheme, which can be applied to any or all types of tools. Consequently, a detailed proof of principle is proposed for just one selected tool type; and this can be considered towards further potential business.

For the initial assessment, the selected tool is from ‘Rennsteig Werkzeuge GmbH’; this is a tool that is used in both, the aerospace and the military sector. This hand-crimping tool is specially developed to process highly-sophisticated aluminium wire terminations. This termination is a closed-barrel terminal, as described in section 2.3.1.2. Such crimp joints are terminated using a four-indent crimp geometry.

The tool comprises a double-sequence crimp process that is composed of a four-indent crimp mechanism and a so-called ‘rosette-crimp’ mechanism. Once the four-indent crimp process is executed at a defined terminal section, then the rosette-crimp is applied to the terminal’s end, so that the insulation and the barrel are crimped in a gas-tight fashion.

Such rosette-crimp scheme specifies a gas-tight connection between wire insulation and the barrel. This sealing feature is indispensable for crimped wire terminations, which comprise an aluminium wire core.

Figure 7.1 shows the aluminium tool from the company: ‘Rennsteig Werkzeuge GmbH’ [37].

Figure 7.1: Aluminium hand-crimping tool from 'Rennsteig Werkzeuge GmbH' **[38]**

7.3.2 Sensor Positioning

The mechanical manipulation to the benefit of environmental optimisation is not considered to be the fundamental aim of this project. Rather, the aim is to provide an easy and flexible CFM upgrade to hand tools, without any significant inconvenience. Thus, each component needs to be adapted to the tool's given geometrical forms, without influencing the tool's performance.

With due consideration to the positioning of all components, many considerations were taken into account, with the assessment carried out strictly based on empirical and experimental operations.

7.3.2.1 Force

The strain gauge, which was described in section 4.4.1.2 is used to analyse the tool's material tension, during the actual crimping operation.

It is required to apply strain gauges onto certain location spots, which are readily accessible, without changing the tool's original mechanical behaviour.

The coupling bars on the tool are used to transfer the radial movement of the tool arms to drive the crimping mechanism. These arms seem to be the most suitable components, to which to attach sensors, which will be proportionally stressed by a crimp force that is relative to the load. Both coupling bars are shown in Figure 7.2.

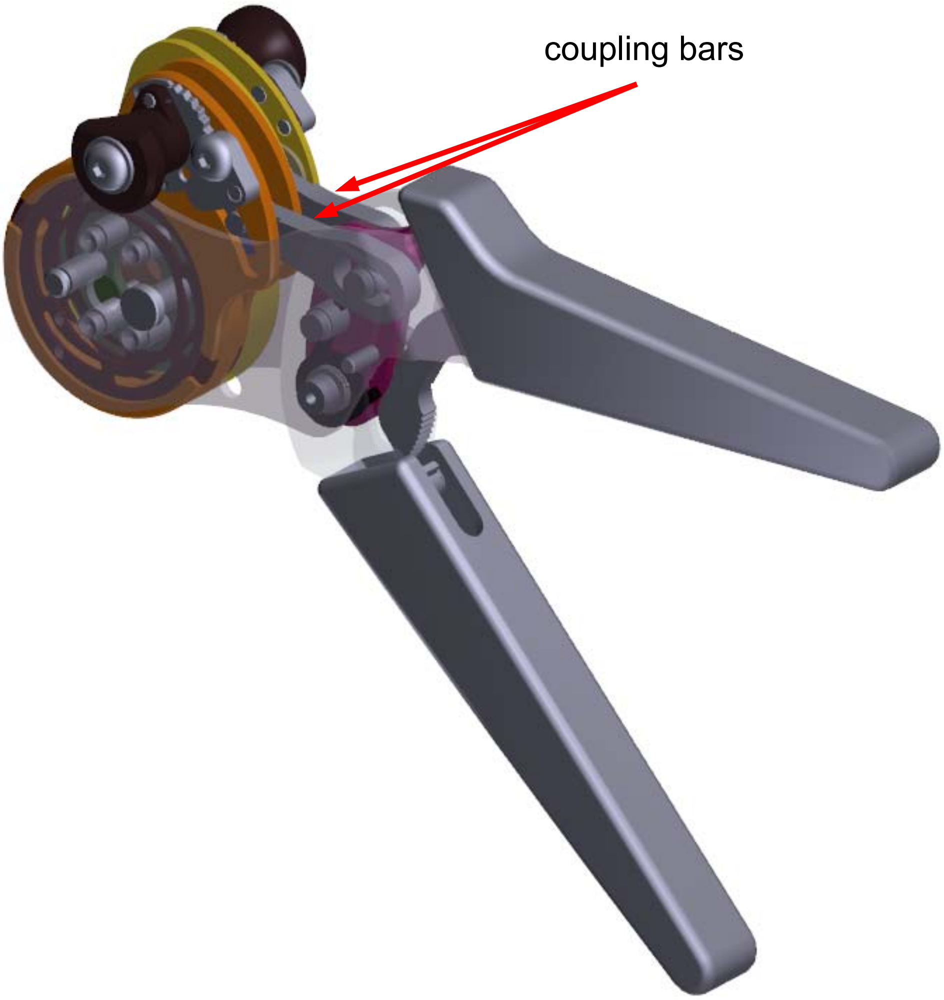


Figure 7.2: Coupling bars of the RWZ crimping tool

For the case in hand, two strain gauges are applied on the upper surface of the coupling bars. Using two strain gauges leads to a double channel measurement, i.e. both strain gauges are read out individually, but combined result is achieved.

Figure 7.3 shows the application of two strain gauges on the surface of the coupling bars.

Figure 7.3: Coupling bars with strain gauge application

By the use of this approach, which is described in Chapter 4, the relative ‘force-over-time’ diagram can be generated. This is shown in Figure 7.4.

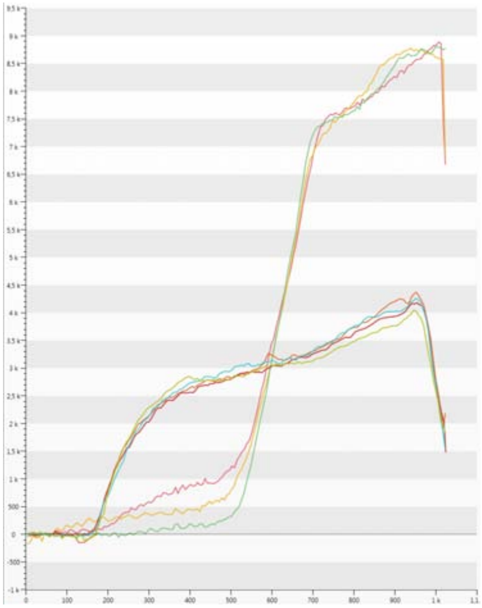


Figure 7.4: Force-over-time diagram of strain gauges, applied on coupling bars

7.3.2.2 Stroke

The positioning of various stroke sensors, which are described in chapter 4.4.2, was decided on the basis of the axis of rotation for the tool's levers. Due to this fact, only rotational-working measuring instruments were taken into account for the initial solution, and a more expensive magnetic angle sensor was also considered.

7.3.2.2.1 Rotary Potentiometer

There are two different kinds of rotary potentiometer technologies, which might be considered for this type of application. The difference in the types is classified by the resistive material, i.e. wire-wound potentiometer and a conductive-plastic potentiometer. To establish which type is best qualified in terms of measurement accuracy, the following evaluation was carried out.

The aim is to determine the relative measurement uncertainty of both technologies, using the prototype tool from 'Rennsteig Werkzeuge GmbH' as a comparable test application.

Figure 7.5 shows the testing application for both potentiometer variants, which are attached to the tool of ‘Rennsteig Werkzeuge GmbH’.

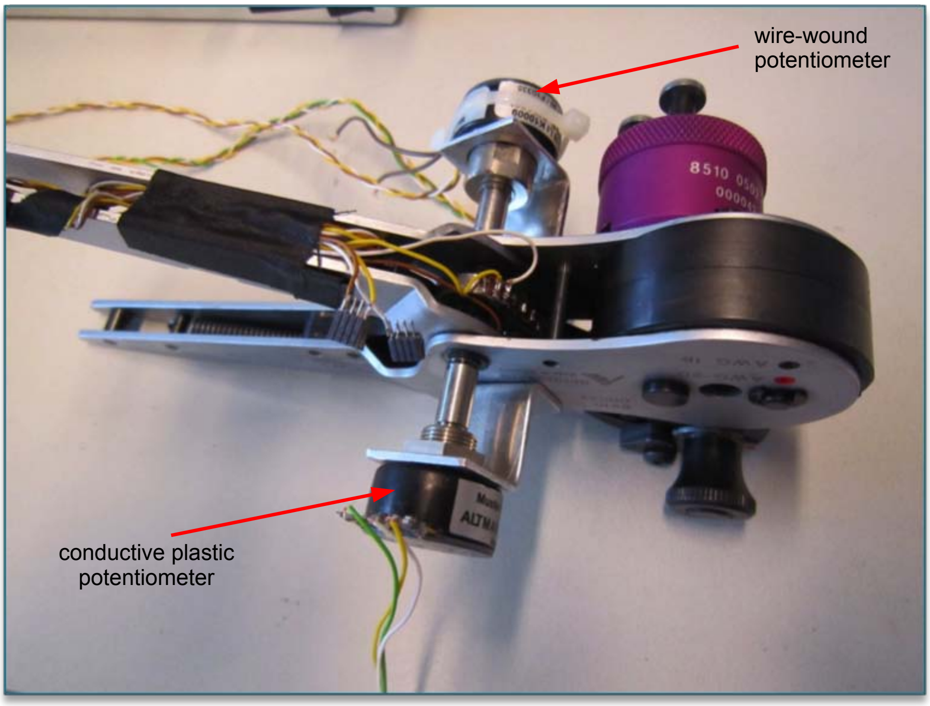


Figure 7.5: Potentiometer testing application

For a mathematical consideration, there is a detailed principle, which is defined by the ‘Joint Committee for Guides in Metrology’ (JCGM) [39]. Their ‘Guide to the expression of uncertainty in measurement’ (GUM) helps to determine the relative uncertainty schematically.

Figure 7.6 shows the analysis principle, from the JCGM 100:2008, in a schematic manner [39].

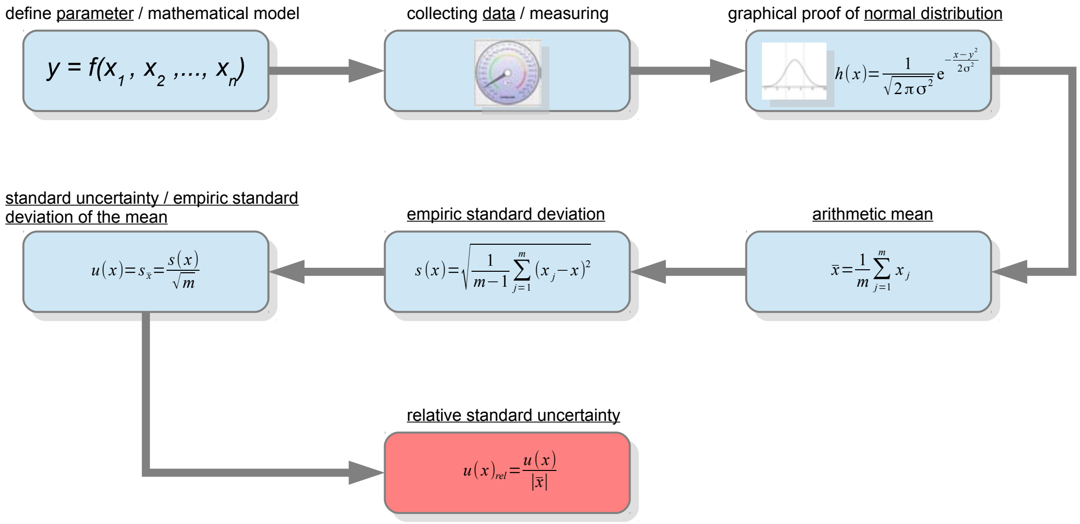


Figure 7.6: Schematic principle: ‘Guide to the expression of uncertainty in measurement’**[39]**

The fundamental basis of considering the relative uncertainty is the existence of the Gaussian normal distribution model for the measurement of data, as shown in Figure 7.7. The assessment of results, based on this approach, requires a graphical interpretation.

In the first instance, the maximum and the minimum value of all measurements need to be figured out. Secondly, the relative range in between is determined, as follows:

$$\Delta x_{\max} = x_{\max} - x_{\min} \tag{5.1}$$

Subsequently, to differentiate all measurement data into classes, the broad number is determined by extracting the square root of the quantity of measurements, as follows:

$$p \approx \sqrt{m} \tag{5.2}$$

The class width is the final step to assess the Gaussian normal distribution graphically, as follows:

$$\Delta x = \frac{\Delta x_{\max}}{p} \tag{5.3}$$

Figure 7.7 shows an example of the graphical representation for a normal distribution.

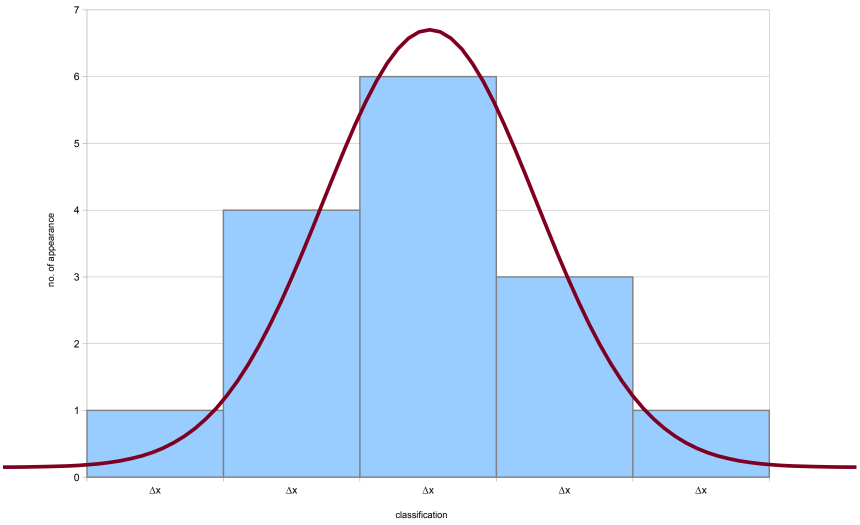


Figure 7.7: Graphical representation for a Gaussian normal distribution

For the actual testing, for both potentiometer types the graphical assessment of Gaussian normal distribution was processed. In so doing, both types were subjected to similar testing operations as a basis for comparing the measurement values of both potentiometers. The values were measured and recorded repeatedly, with the tool in a defined condition. The mechanical ratchet mechanism of the tool proved to be an ideal location to generate reliable test conditions, by keeping the tool in the same ratchet position, all the time. For this investigation, the tool was held at five ratchet steps while closing. This was repeated 50 times.

The complete analysis to determine the relative uncertainty in measurement for both potentiometer types was carried out as follows.

The measurement classification for the wire-wound potentiometer is shown in Table 7.1.

Wire-wound potentiometer:

m	*50*
maximum value	*3.1260 kΩ*
minimum value	*3.1230 kΩ*
Δx_{max}	*0.0030 kΩ*
p	*≈8*
Δx	*0.0004 kΩ*

classification	m_C *(appearance per class)*	P_C *(probability)*
class 1	*0*	*0.00*
class 2	*1*	*0.02*
class 3	*6*	*0.12*
class 4	*18*	*0.36*
class 5	*14*	*0.28*
class 6	*5*	*0.10*
class 7	*4*	*0.08*
class 8	*2*	*0.04*

Table 7.1: Measurement classification for wire-wound potentiometer

The measurement classification leads to the graphical representation of normal distribution of all measurements, as shown in Figure 7.8.

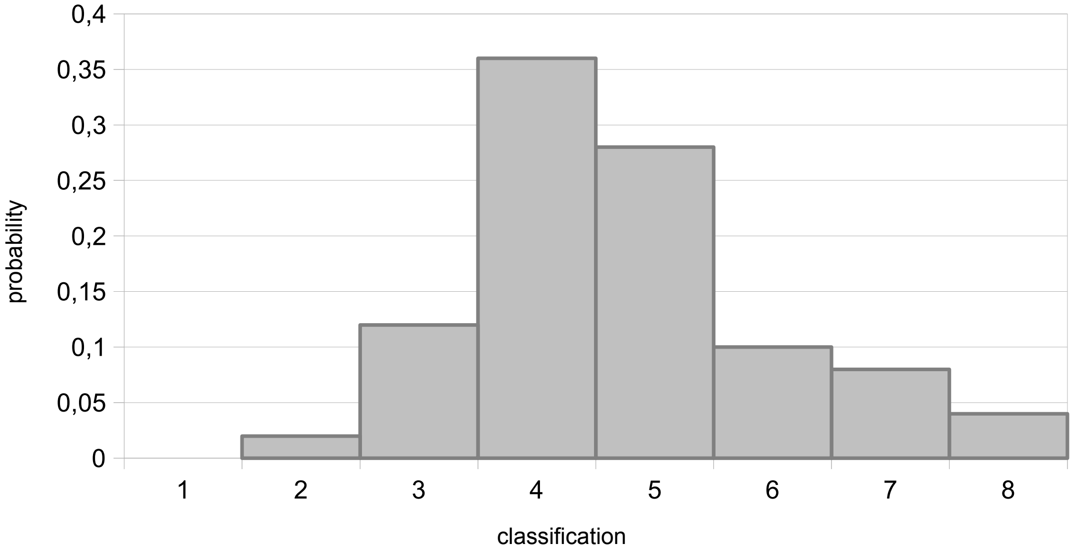


Figure 7.8: Graphical representation of normal distribution for wire-wound potentiometer

Subsequent to this representation, the determination of the relative uncertainty can be done. Initially the arithmetic mean needs to be determined, as follows:

$$\bar{x} = \frac{1}{m}\sum_{j=1}^{m} x_j = 3.1239k\Omega \tag{5.4}$$

On the basis of Formula 5.4 the empiric standard deviation can be figured out, as follows:

$$s(x) = \sqrt{\frac{1}{m}\sum_{j=1}^{m}(x_j - \bar{x})^2} = 0.0010k\Omega \tag{5.5}$$

Using the empiric standard deviation (Formula 5.5), the standard uncertainty, also called empiric standard deviation of the mean, can be specified, as follows:

$$u(x) = s_{\bar{x}} = \frac{s(x)}{\sqrt{m}} = \frac{0.0010}{\sqrt{50}} = 0.0001414k\Omega = 0.1414\Omega \tag{5.6}$$

Finally, the relative standard uncertainty can be determined:

$$u(x)_{rel} = \frac{u(x)}{|\bar{x}|} = 0.000045 = 0.0045\% \tag{5.7}$$

With the aim of comparing the two different potentiometer types, by determining their relative uncertainty in measurement, the same procedure is projected onto the conductive plastic potentiometer.

<u>Conductive plastic potentiometer:</u>

Table 7.2 shows the measurement classification for the conductive plastic potentiometer.

m	*50*
maximum value	*2.6800 kΩ*
minimum value	*2.6150 kΩ*
Δx_{max}	*0.0650 kΩ*
p	*≈8*
Δx	*0.0081 kΩ*

classification	m_C *(appearance per class)*	P_C *(probability)*
class 1	*4*	*0.00*
class 2	*7*	*0.02*
class 3	*11*	*0.12*
class 4	*14*	*0.36*
class 5	*10*	*0.28*
class 6	*2*	*0.10*
class 7	*0*	*0.08*
class 8	*2*	*0.04*

Table 7.2: Measurement classification for conductive plastic potentiometer

The relevant diagram to graphically represent the normal distribution can be found in Figure 7.9.

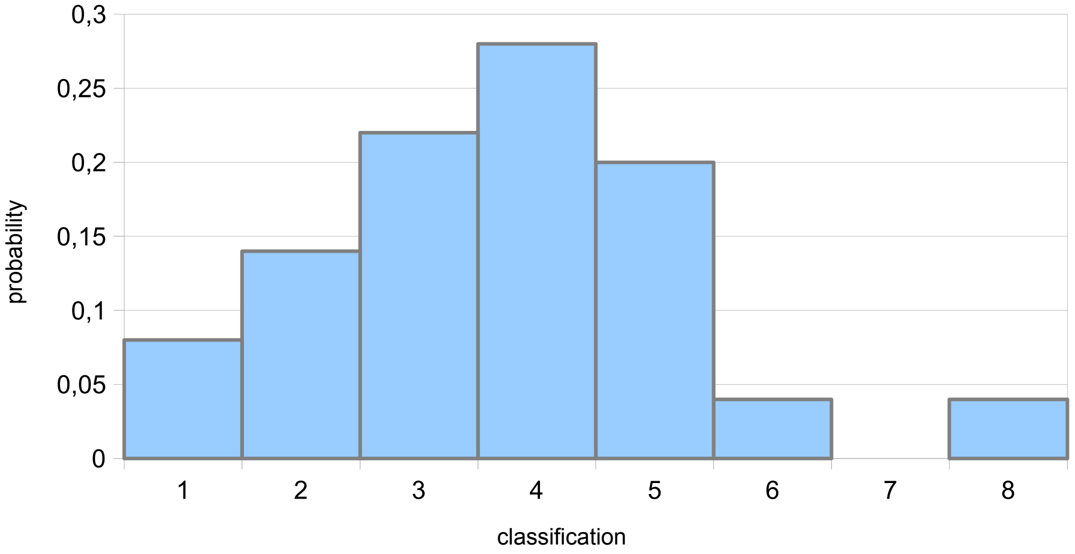


Figure 7.9: Graphical representation of normal distribution for conductive plastic potentiometer

The analysis of the relative uncertainty in measurement is done in an identical way as for wire-wound potentiometer.

At first the arithmetic mean is most relevant:

$$\bar{x} = \frac{1}{m}\sum_{j=1}^{m} x_j = 2.6407 k\Omega \tag{5.8}$$

Formula 5.8 leads to the empiric standard deviation:

$$s(x) = \sqrt{\frac{1}{m}\sum_{j=1}^{m}(x_j - \bar{x})^2} = 0.0128 k\Omega \tag{5.9}$$

Subsequently, the standard uncertainty can be determined:

$$u(x) = s_{\bar{x}} = \frac{s(x)}{\sqrt{m}} = \frac{0.0128}{\sqrt{50}} = 0.001810 k\Omega = 1.810\Omega \tag{5.10}$$

And the relative standard uncertainty in measurement for conductive plastic potentiometer is as follows, showing the rounded result:

$$u(x)_{rel} = \frac{u(x)}{|\bar{x}|} = 0.0006855 = 0.069\% \tag{5.11}$$

<u>Conclusion comparison:</u>

The relative uncertainty in measurement for wire-wound potentiometer is less than for that of conductive plastic-potentiometer. In total the wire-wound potentiometer is more than 15 times more precise as compared to the conductive plastic potentiometer. Consequently, the conductive plastic potentiometer is withdrawn from application.

7.3.2.2.2 Magnetic Angle Sensor

The magnetic angle sensor PRAS21 from ASM GmbH [28], as described previously, is attached to the same rotary mounted metal bolt as is was shown for the potentiometers. The scheme provides a very neat solution due to the sensor’s small dimensions and its non-contact behaviour. The magnet target is simply attached to the bolt by a single screw as shown in Figure 7.10.

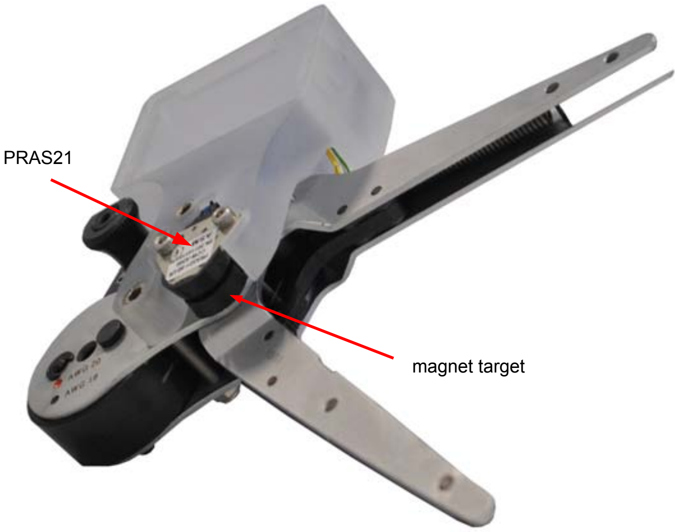


Figure 7.10: Magnet angle sensor PRAS21 positioning

Since it is accepted from the specification that this type of sensor is highly precise, and is reliably mechanically attached to the crimping tool, a detailed investigation in regard to the measurement of uncertainty was not deemed to be necessary.

In summary, the magnetic angle sensor is the preferred technical solution due to its advantages such as higher precision, wear-free operation, and the stable and simple mounting arrangements. However, a potentiometer-based solution would be cheaper, although technically inferior. On balance, the author recommends the qualification of the PRAS21 magnet angle sensor.

7.3.3 Housing / Application

Some of the above discussion has illustrated how sensor components are positioned and applied to the RWZ tool. Following on from that, this subsection will describe how all of the system components are attached and integrated into the hand crimping tool; with a view to extending the tool’s feature set to realise a highly sophisticated crimp force monitoring scheme. A full enclosure/housing design for a bold-on product that will upgrade an RWZ hand tool to a full featured CFM system will be described.

Throughout the development process, consideration must be given to the ergonomic aspects of the design; so that the tool operator can feel comfortable with the repetitive use of the tool, with continued good quality results. The product design of the housing for various components, such as the various sensors, the PCB, the battery etc. must be compact and lightweight in its construction.

Components must be positioned so as to avoid any possible mechanical obstructions or other side-effect influences on the operation of the tool.

Three different variants of the design were considered. A former undergraduate student, working under the guidance of the author in this project, did the complete design work as part of his Bachelor thesis [40]. Each one of these variants can be briefly summarised in the following subsections, listing a summary of the strengths and weaknesses.

7.3.3.1 Variant 1

Figure 7.11 illustrates ‘variant 1’ for the prototype physical housing design [40]. This design provides a tool upgrade solution, which requires some modification of the tool. The design is neat and compact. However, the tool will have an unbalanced feel due to its suboptimal centre of mass location. A top-level list of some strengths and weaknesses is provided below.

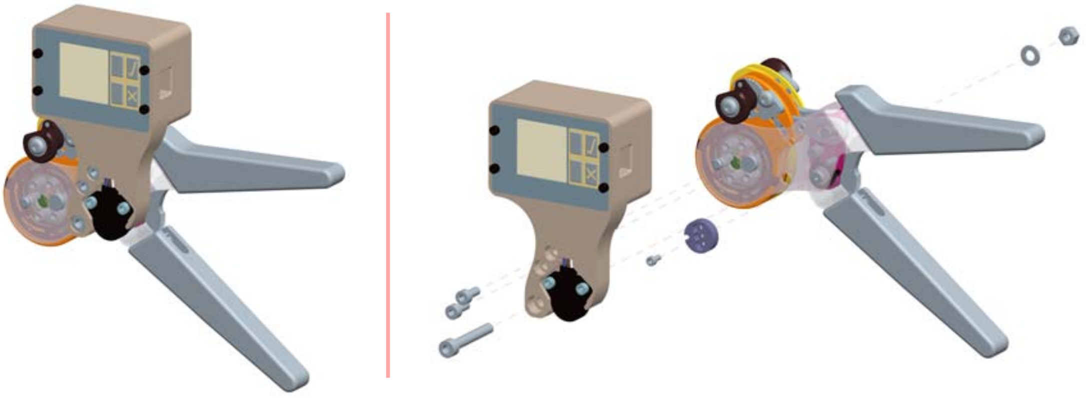


Figure 7.11: CFM-housing: variant 1 **[40]**

Strengths:

- No tool modification is necessary
- Very stable fixation of stroke sensor is realised in a compact design
- Good protective covering of strain gauges
- Compact design
- Short wirings

Weaknesses:

- Resulting inconvenient centre of mass of the whole tool

7.3.3.2 Variant 2

Figure 7.12 illustrates ‘variant 2’ for the prototype physical housing design. This design provides a tool upgrade solution, which requires some modification of the tool. The tool will be rather cumbersome but will have a balance feel. A top-level list of some strengths and weaknesses is provided below.

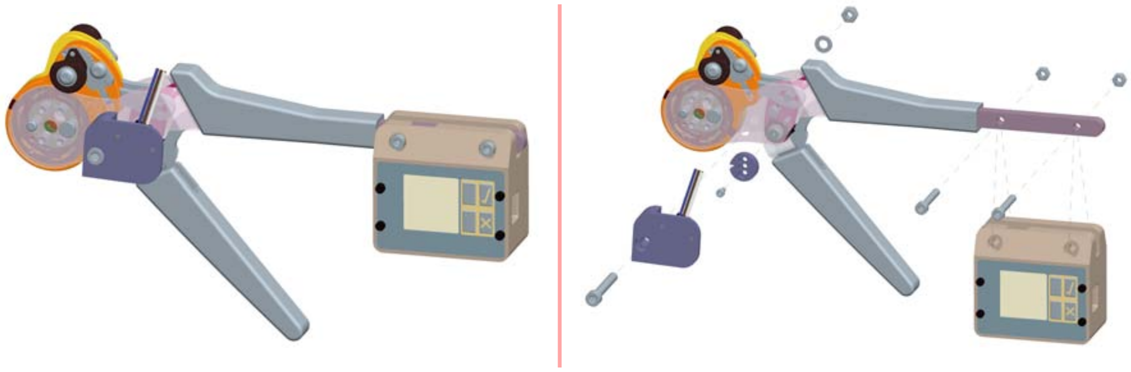


Figure 7.12: CFM-housing variant 2 **[40]**

Strengths:

- Convenient centre of mass of the whole tool is realised
- Simple design

Weaknesses:

- Tool modification is necessary
- Not a compact design
- Elaborate and long wiring requirements
- No protection of strain gauges

7.3.3.3 Variant 3

Figure 7.13 illustrates ‘variant 3’ for a prototype physical housing design. This design allows a tool upgrade without a modification to the basic tool. However, it is a cumbersome solution, with no protection of the strain gauges, and the tool has an unbalanced feel. A top-level list of some strengths and weaknesses is provided below.

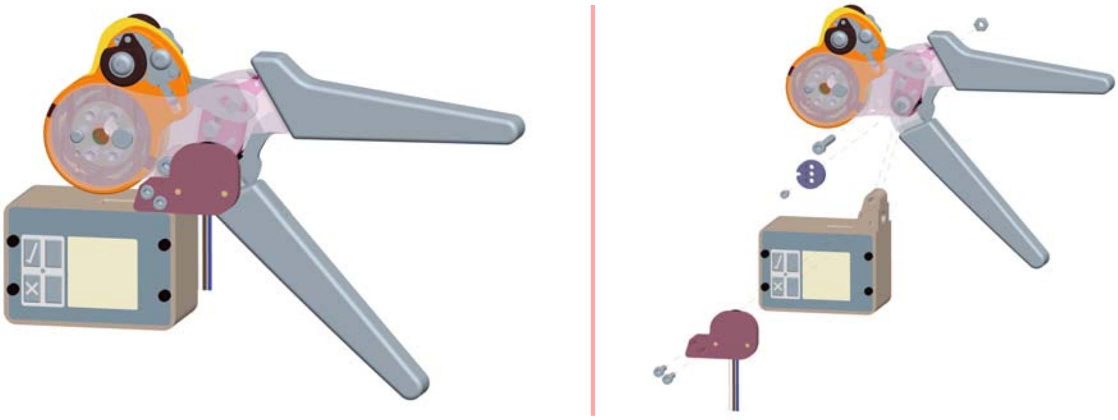


Figure 7.13: CFM-housing variant 3

Strengths:

- Simple design
- No tool modification is necessary
- Short wirings

Weaknesses:

- Inconvenient centre of mass of the whole tool

- No protection of strain gauges

7.3.3.4 Conclusion on the Physical Design

A use-value analysis was carried out to help decide on which of these variants might be the most suitable for the best functionality and most comfortable tool handling. Table 7.3 summarises some of the key points from the use-value analysis.

criterion	weighting in %	*variant 1*			*variant 2*			*variant 3*		
		valuation	value	weighted value	valuation	value	weighted value	valuation	value	weighted value
complexity	25	minor	3	0.75	medium	2	0.5	medium	2	0.5
effort of tool modification	25	minor	3	0.75	medium	2	0.5	minor	3	0.75
strain gauge protection	20	high	4	0.8	low	1	0.2	low	1	0.2
mountable	15	simple	3	0.45	simple	3	0.45	v. simple	4	0.6
required space	10	minor	3	0.3	medium	2	0.2	minor	3	0.3
design	5	very good	4	0.2	good	3	0.15	good	3	0.15
total	100	+		3.25	-		2.0	-		2.5

Table 7.3: Use-value analysis **[40]**

In the context to this analysis ‘variant 1’ is deemed to be the most adequate for the CFM application. However, it is understood that this ‘variant 1’ does have some shortcomings but it is probably the best compromise solution. In future products manufacturers may elect to do a full feature tool design rather that employing a retrofit approach.

7.4 EMC Testing

The electromagnetic compatibility (EMC) investigation was executed in a rather early stage of the development so as to be able to anticipate any potentially critical chip positioning or EMC-hostile conducting paths in the various layouts and configurations.

Considering these matter, the EMC assessment is related to the electrical function block, rather that to the entire crimping system.

The EMC test was carried out at the University of Applied Sciences in Deggendorf. The investigation was based on the relevant industrial norms: EN 61000-6-2 and EN 61000-6-4.

7.4.1 Transient Emission as per EN 61000-6-4

The investigation of the transient emission of an embedded system requires an analysis of the strength of electromagnetic interference while the system is in operation. The rating, on whether the electromagnetic emission is below a certain threshold value, is based on the specifications of the industrial norm: EN 61000-6-4.

For the purposes of this evaluation the system should operate in its general operational situation, or as close to a normal situation as is practically possible.

For this investigation the crimp force monitoring system was programmed to transfer force and stroke values, continuously, via USB to the PC workstation. The power supply of the embedded system is realised using the USB port.

For each transient emission test configuration, the test system includes the same configuration for tool, strain gauge, stroke sensor, and PCB.

The schematic setup for the transient emission testing is shown in Figure 7.14.

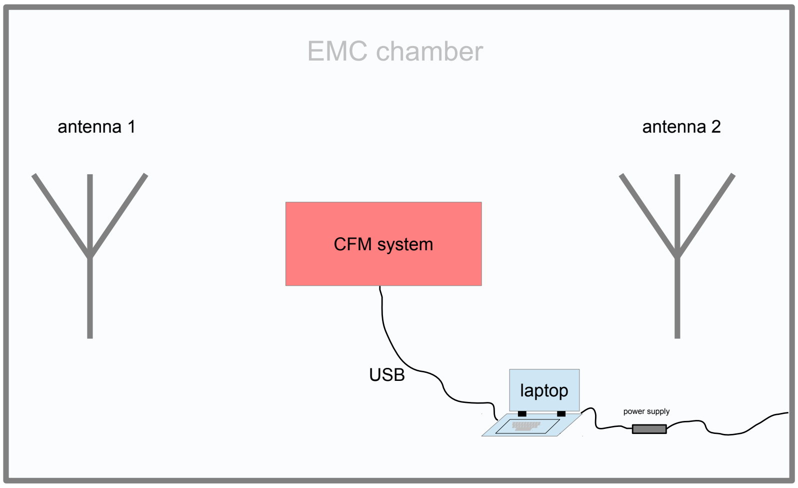


Figure 7.14: Schematic setup of EMC chamber for transient emission investigation

The investigation of the transient emission (TE) was carried out three times with three different preconditions.

7.4.1.1 First TE Measurement

For the first test, the preconditions are listed below and the results graph is shown in Figure 7.15.

Preconditions

Polarisation:	horizontal
Items inside the chamber:	laptop including the power supply unit and the embedded system mounted on RWZ tool
Power supply of the CFM system:	5m shielded USB cable
Strain gauge wiring:	shielded cable

Resulting frequency-response diagram:

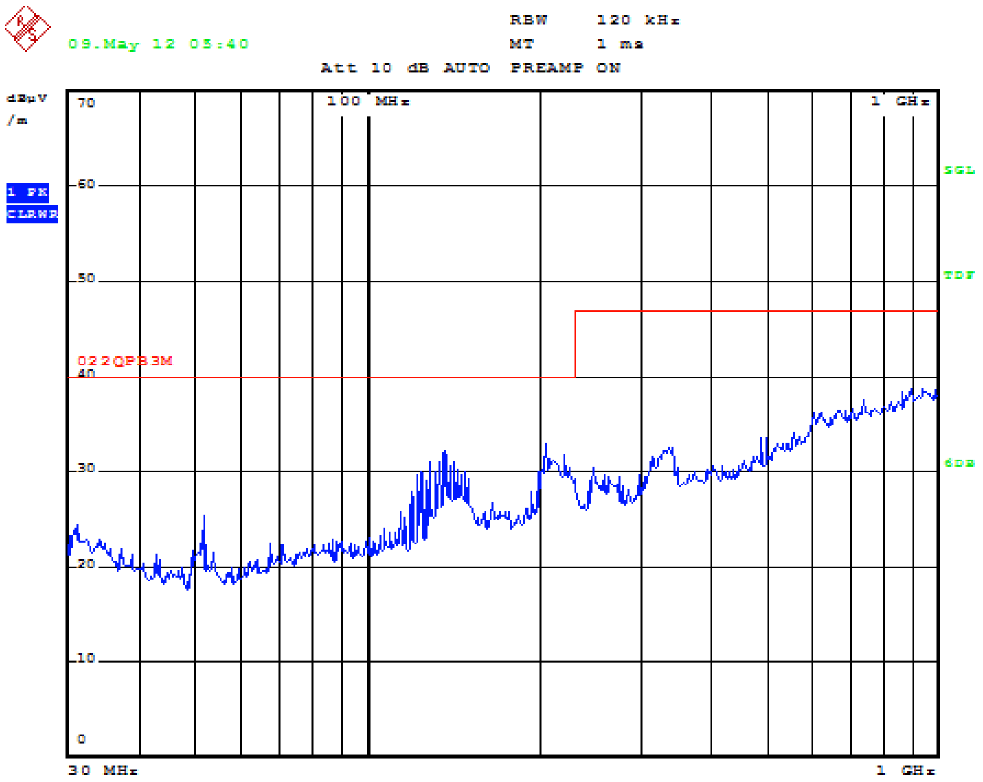


Figure 7.15: Frequency-response diagram of the first TE measurement

Conclusion:

The measured electromagnetic interference (EMI) peak is below the threshold value, which is highlighted in red in Figure 7.15.

7.4.1.2 Second TE Measurement

For the second test, the preconditions are listed below and the results graph is shown in Figure 7.16.

Preconditions:

Polarisation: vertical

Items inside the chamber:	laptop including the power supply unit and the embedded system mounted on RWZ tool
Power supply of the CFM system:	5m shielded USB cable
Strain gauge wiring:	shielded cable

Resulting frequency-response diagram:

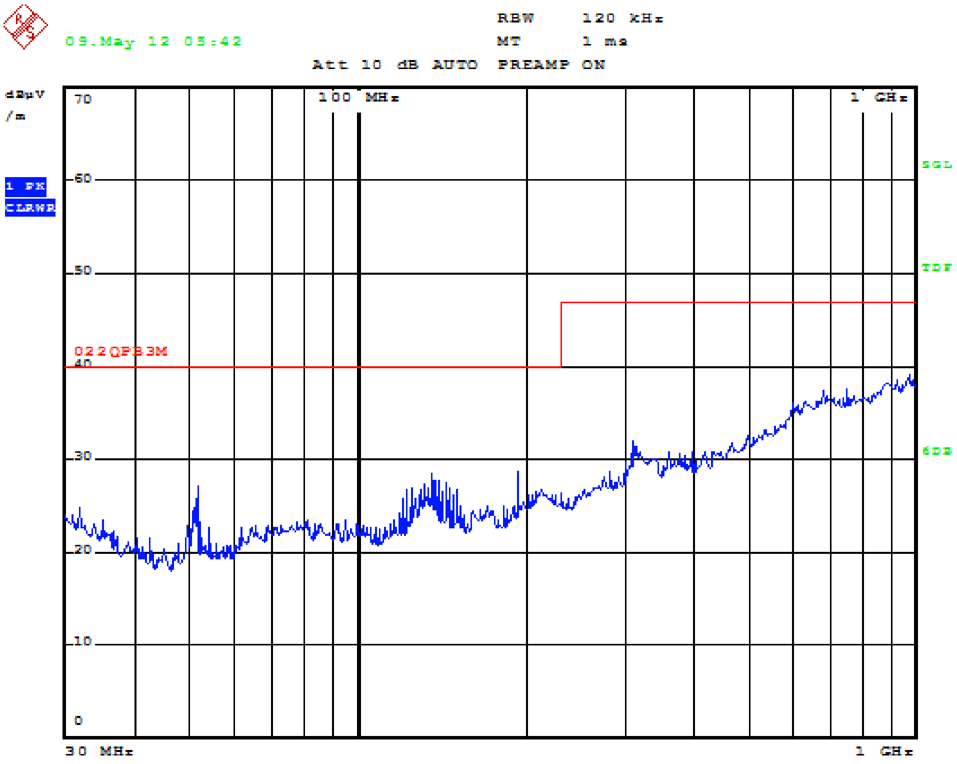


Figure 7.16: Frequency-response diagram of the second TE measurement

Conclusion:

The measured electromagnetic interference (EMI) peak is below the threshold value, which is highlighted in red in Figure 7.16.

7.4.1.3 Third TE Measurement

For the third test, the preconditions are listed below and the results graph is shown in Figure 7.17.

Preconditions

Polarisation:	horizontal
Items inside the chamber:	laptop including the power supply unit and the embedded system mounted on RWZ tool
Power supply of the CFM system:	5m shielded USB cable
Strain gauge wiring:	unshielded cable

Resulting frequency-response diagram:

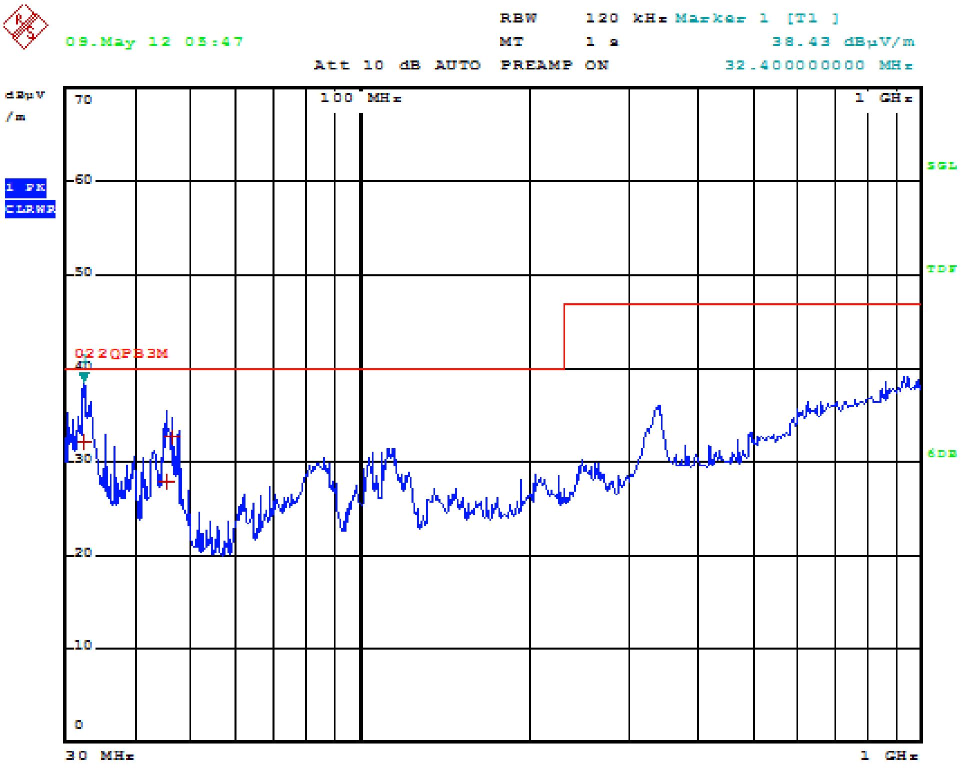


Figure 7.17: Frequency-response diagram of the third TE measurement

Conclusion:

The measured electromagnetic interference (EMI) peak is below the threshold value, which is highlighted red in Figure 7.17. Note, the peak in between the frequency points, 30 and 50 MHz, is some 7.33dB below the threshold value.

7.4.2 Immunity to Interference as per EN 61000-6-2

Testing an embedded system for immunity to interference, as per norm: EN 61000-6-2, requires an analysis of the system's sensitivity in terms of interfering electromagnetic signals.

For this assessment, the CFM system was programmed to 'continuously' transfer both of the digitised sensor signals, via USB, to the Laptop; as was the case for the transient emission measurement. However, in this case the Laptop was outside of the chamber and connected to the embedded system using a USB cable.

The schematic setup for the immunity to interference measurement can be seen in Figure 7.18.

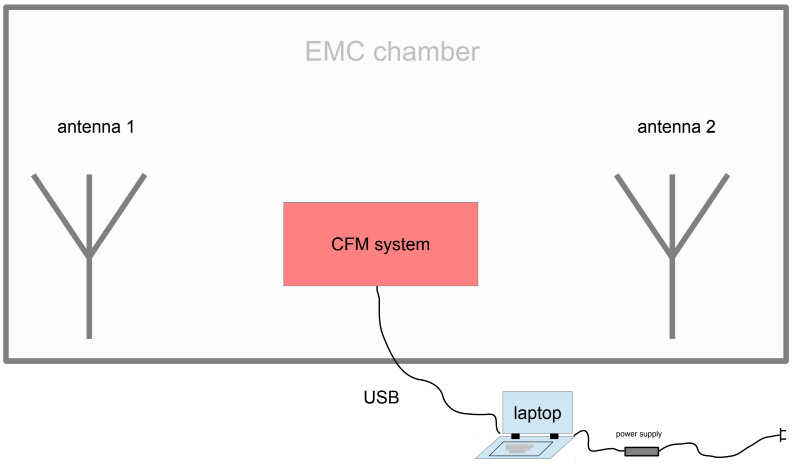


Figure 7.18: Schematic setup of the EMC chamber for immunity to interference investigation

The investigation was carried out with different electromagnetic polarisations, as summarised in the following subsections.

7.4.2.1 First Immunity to Interference Measurement

For the first investigation, the preconditions are listed below and the results are summarised.

Preconditions

Polarisation:	horizontal
Items inside the chamber:	embedded system applied to RWZ tool
Items outside the chamber:	laptop includes the power supply unit
Power supply of the CFM system:	shielded USB cable
Strain gauge wiring:	shielded cable

Result:

The force signals as well as the stroke signal were not unduly affected. The stroke value was fluctuating with a maximum range of plus/minus 10 digits.

Conclusion:

The coupling of interfering signals had no negative effects on the functionality of the embedded system.

7.4.2.2 Second Immunity to Interference Measurement

For the second investigation, the preconditions are listed below and the results are summarised.

Preconditions

Polarisation:	horizontal + vertical
Items inside the chamber:	embedded system applied to RWZ tool
Items outside the chamber:	laptop includes the power supply unit
Power supply of the CFM system:	shielded USB cable
Strain gauge wiring:	shielded cable

Result:

The digitised sensor signal of the stroke sensor was noted to be able to read out permanently without any negative effects.

Both strain gauges, which are applied to the coupling bars as described in the previous chapter, exhibited different behaviours while the interfering signal was applied. After a short but detailed inspection it was obvious that this difference was caused by different hardware conditions. One of the strain gauges was not connected to an analog low-pass filter. This strain gauge channel, without a low-pass filter, was seriously affected by the interfering signal, which led to a voltage-offset drift of more than 8000 digits.

The strain gauge channel, which was wired with the low-pass filter, had no serious problems.

Conclusion:

To withstand such disturbances, each single strain gauge needs to be wired with the relevant low-pass filter.

7.5 Summary

This chapter provides the evaluation of a selected prototype tool, the ‘Rennsteig Werkzeuge GmbH’ tool, as a candidate tool for assessment of the project. The key aims were to find the most adequate mounting location on the prototype’s mechanism, for both sensors, the strain gauges and the stroke-sensor. Furthermore, a detailed statistical comparison of two candidate stroke sensors was carried out to allow a decision of which sensor type should be qualified for the application.

Various physical CFM-housing design variants were investigated, in order to compare relevant strengths and weaknesses of the different design approaches.

Finally, the results of the EMC investigation are summarised, where the results are encouraging towards the continued development of a product that will be usable in a typical industrial environment, without being affected by electromagnetic disturbances.

8 Conclusions and Continuation Work

This chapter summarises the results of the research project and assesses the actual achievements against the original project aims and objectives.

In respect to the automotive industry, there is an obvious demand for dependable and trustworthy products; and as an integral part of that, there is the ongoing requirement for assuring the quality of cable connections, based on the implementation of best practices which are governed by published guiding principles. Defective cable terminations can damage a company's reputation and, worse, may lead to road traffic accidents. For the case of the aircraft industry, similar quality problems may give rise to even more drastic consequences, even leading to massive destruction with fatal consequences. It is hoped that this research project, in its own small way, might play a part in the improvement of quality practices on cable production; by providing enhanced tools and instrumentation that might encourage the industry to break away from the old-fashioned practices and structures for wire crimping production equipment.

8.1 Review of the Achievements

This research work includes a detailed review of the state-of-the-art crimp force monitoring schemes for stationary crimping machines. A new concept is then proposed for the design and development of an enhanced CFM scheme, which can be attached to mobile crimping tools. Beginning with a review and assessment of measurement technologies that can be positioned right onto the tool, a full prototype solution was then developed, which included a thorough evaluation of the various subsystems, and led to the assessment of the resulting digitised signal that represents the behaviour of the crimp operation. Such achievements are in line with the original key objectives for the entire research project, which are stated in section 1.3.

The qualification and testing tasks of the resulting prototype was carried out in a formalised fashion, where the detailed activities and results are described in Chapter 7: ‘Prototype Construction, Evaluation, Validation and Testing’.

The proposed concept has already been presented to some key market players, which have already agreed to evaluate the prototype product on a ‘beta test’ basis. Thus, some of the first early devices are now in the production phase.

The project achievements can be briefly summarised as follows:

- A detailed review of the technical practices in the current cable termination business was carried out. Such a review in this specialised technology area has not been done previously, or at least such work has not be found in the published literature.
- A comprehensive investigation of the state-of-the-art crimp force monitoring schemes and technologies was carried out. The investigation highlighted and described current practices so that the proposed new solution could be developed based on the previous knowledge.
- A fully functional sensor component subsystem was developed for the CFM solution, for application to hand tools.
- Analytical and statistical measurement and assessment algorithms were developed to a standard, which allows a final quality rating to be applied to crimped joint connections. Such algorithms are designed to be embedded directly onto the instrument’s microcomputer. This is a significant achievement in relation to the feasibility of the project.
- A new specialised microcontroller system was developed, which is able to integrate all of the required computing; including the signal processing, the algorithms, the storage, and the I/O interfaces.
- A comprehensive evaluation of a prototype CFM instrument was carried out, as a retrofit solution based on a selected hand-held crimping tool.

- Finally, and beyond the original project objectives, a production run of the prototype instrument was instigated based on agreement with some industrial companies to evaluate the concept in some real production environments.

8.2 Continuation Work

This research work has been successful in proposing a new concept, within the CFM context, and has developed a prototype tool to demonstrate the feasibility of that concept. A lot of knowledge has been gained in the course of the project work and now that a prototype tool device is available the next step is to further assess the feasibility of the scheme by verifying the usefulness of the solution through a comprehensive set of managed field tests.

To move to the next step it will be very important to enlist the additional services of a specialised contractor to work out a scheme for the optimal integrated manufacture and assembly of the very fine strain gauge, so that the proposed tool can be technically ready to handle any potential volume production orders.

The current production run of ‘beta test’ tools is considered to be at a ‘pre-product’ stage of development. Once a satisfactory ‘close-to-production’ prototype is realised, then more comprehensive assessments and investigations can proceed in terms of the high-volume evaluation of quality operation of the tool under various climatic conditions and other industrial environmental considerations. Further detailed EMC evaluation will also need to be carried out.

It is planned that the first field tests in cooperation with the aerospace industry will start at the end of 2013.

8.3 Knowledge Gained from this Research Project

Although the author, at the beginning of the project, already had a good basic comprehensive understanding of the main scientific and technical aspects of the topic, a much more detailed and richer understanding was gained in the course of the research work, in relation to the specialised field of high-quality cable production, as well as the associated quality assurance standards. The applied techniques and algorithms to assess and rate a crimp process's quality level were especially new.

A completely new and unknown experience for the author was that of leading a project team consisting of various undergraduate students. During the course of this project, periodic meetings had to be arranged to review the research project status, synchronise results, and to discuss further plans and prospects.

Additionally, there was the need to present the research work and its results to potential future commercial users. Thus, new skills were learned for presenting detailed technical information to commercially minded audiences.

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