Design and Construction of A Novel Reconfigurable Micro Manufacturing Cell

By

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Abstract

Demands for producing small components are increasing. Such components are usually produced using large-size conventional machining tools. This results in the inadequate usage of resources, including energy, space and time. In the 1990s, the concept of a microfactory was introduced in order to achieve better usage of these resources by scaling down the size of the machine tool itself. Several industries can benefit from implementing such a concept, such as the medical, automotive and electronics industries. A novel architecture for a reconfigurable micro-manufacturing cell (RMC) is presented in this research, aiming at delivering certain manufacturing strategies such as point of use (POU) and cellular manufacturing (CM) as well as several capabilities, including modularity, reconfigurability, mobility and upgradability. Unlike conventional machine tools, the proposed design is capable of providing several machining processes within a small footprint (500 mm^2), yet processing parts within a volume up to 100 mm^3. In addition, it delivers a rapid structure and process reconfiguration while achieving a micromachining level of accuracy.

The approach followed in developing the system is highly iterative with several feedback loops. It was deemed necessary to adopt such an approach to ensure that not only was the design relevant, but also that it progresses the state-of-the-art and takes into account the many considerations in machine design. Following this approach, several design iterations have been developed before reaching a final design that is capable of delivering the required manufacturing qualities and operational performance.

A prototype has been built based on the specifications of the selected design iteration, followed by providing a detailed material and components selection process and assembly method before running a performance assessment analysis of the prototype. At this stage, a correlation between the Finite Element Analysis (FEA) model and prototype has been considered, aiming at studying the level of performance of the RMC when optimising the design in the future. Then, based on the data collected during each stage of the design process, an optimisation process was suggested to improve the overall performance of the system, using computer aided design and modelling (CAD/CAM) tools to generate, analyse and optimise the design.

Acknowledgments

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Abbreviations

2D	Two dimensional
3D	Three dimensional
AHP	Analytical Hyrarichical Process
BOM	Bill of Material
BOP	Bill of Processes
CAD	Computer aided design
CDS	Capacitance Displacement sensor
CM	Cellular Manufacturing
CNC	Computer Numerical Control
CPU	Computer processing unit
DAC	Data acquisition card
DOF	Degree of Freedom
DMS	Dedicated Manufacturing Systems
DMLs	Dedicated-rigid Manufacturing Lines
EDM	Electrical discharge machine
FEA	Finite element analysis
FEM	Finite element Modelling
FMS	Flexible Manufacturing Systems
GT	Group Technology
HZ	Hertz
IC	Integrated Circuit
IT	Information Technology
JIT	Just in Time
MDO	Multidisciplinary Design Optimisation
MEMS	Micro Electromechanical Systems
MM	Micro Manufacturing systems
MPP	Manufacturing Process Planning
MRR	Material Removal Rate
NF	Natural Frequency
PI	Physik Instrumente
RMS	Reconfigurable Manufacturing Systems
RMT	Reconfigurable Machine tool
RPM	Revolutions per minute
PDE	Partial Differential Equation
POC	Point of Care
POU	Point of Use
PnP	Plug and Play

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Chapter 1:
Introduction

Chapter 1 - Introduction

1.1 Manufacturing: An Overview

A manufacturing process can be defined as transforming raw materials into finished goods, which can be done by performing several machining, assembly and transferring processes within a network of activities (Kalpakjian et al, 2003). This process can be shown in the introduction of new manufacturing concepts, machining processes and new levels of precision, aiming at meeting the increased market demand using less resources such as space, energy, lead time and cost. Hence, several manufacturing techniques have been introduced and developed over the past few decades including Just-In-Time, Lean, Agile, and Rapid manufacturing (Melton, 2003).

1.2 Micro-Manufacturing: A Historical Review

Since the invention of transistors in 1947, the technology of micro-electrical manufacturing has been growing rapidly (Masuzawa, 2000). This was followed by the building of the first integrated circuit (IC) in 1958, which resulted in producing even more advanced and integrated silicon-based components, all of which have been increasing in precision and reaching length scales of sub-micron range.

In 1982, the term Micro-Machining was introduced, describing a mechanism that focused on fabricating and producing a new generation of micromechanical parts such as sensors and accelerometers. The introduction of this concept helped to start a new era of mass production of silicon-based micro components (Zhao et al, 2001). However, achieving a high level of precision and production volumes using conventional machine tools was not enough, due to the lack of flexibility on both process and operational levels, as well as the potential cost required to upgrade all or part of the production line in order to cope with future demands (Melton, 2005).

Mishima (2002) explains that Micro-Manufacturing systems are “small scale manufacturing systems which can perform with higher throughput while resource utilisation and energy consumption rate can be reduced simultaneously”. The observation of these advantages and limitations of micro-machining technology has resulted in developing the concept of Microsystems (Mishima, 2007). This new concept gained attention during the late 1980’s (1987-1988), focusing on the miniaturisation of some of the existing fabricating techniques aiming at scaling down the size and increasing the level of productivity of the system. According to Ashida (2000), this approach could allow more compact and more integrated manufacturing systems that can achieve higher production volumes in the future. A schematic diagram in Figure 1.1 shows the development of machining accuracy over the past fifty years.

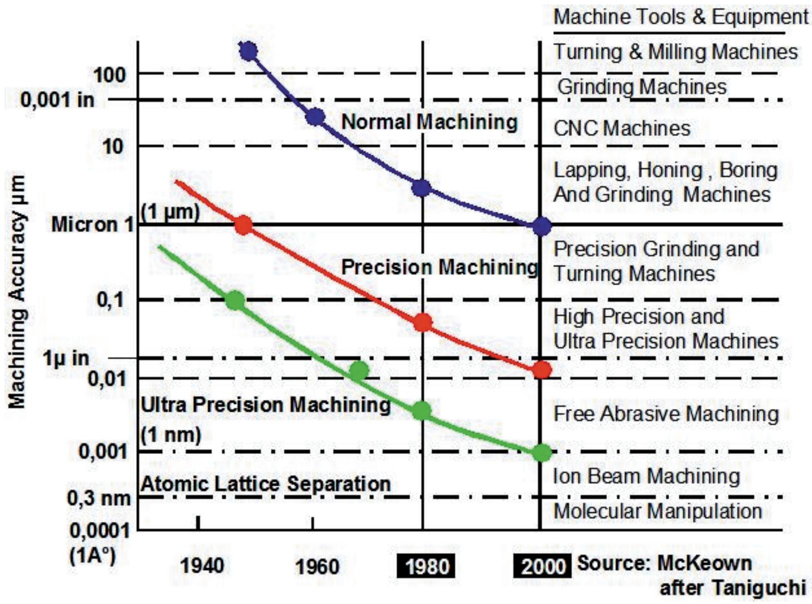


Figure 1.1. Development of machining accuracy (Byrne, 2003).

Over time, the development of Micro-Manufacturing Systems (MMs) has been driven by the need to produce even more precise and higher quality products while introducing and maintaining a satisfactory level of production flexibility (Youssef, 2006). During the past few years, this concept has been used in producing a wide range of products within a number of industries such as automotive, healthcare, military, telecommunication and IT facilities (Fig. 1.2).

Figure 1.2: Applications of micro-manufacturing in industry.

Within the healthcare industry, micro-manufacturing is being used at production level to produce high precision parts such as custom hearing aids and medical implants. Also, micro-manufacturing is widely involved in making medical devices and instruments that can be used in several medical applications. Furthermore, micro-manufacturing has become a standard technique in some industries such as electronics and IT. That can be justified by understanding the factor of competitiveness between IT companies to produce better products in order to increase their market share.

1.3 What Is Micro-Manufacturing?

Micro-manufacturing techniques often refer to non-silicon-based and even non-MEMs-based manufacturing. Micro-manufacturing, in a new category, which can be defined as the manufacture of micro-products and features with scaled-down conventional technologies and processes (Qin et al, 2002). These include processes such as micro-machining (mechanical, thermal, electric-chemical, and electric discharge methods), micro-forming/replication, micro-additive (rapid methods, electro-forming, injection moulding etc.) and joining. Another focus of micro-manufacturing is the manufacture of parts with miniature machine tools, to produce small-scale components with a high level of accuracy, which is potentially related to the machine tool size.

As a new emerging field, the implementation of micro-manufacturing is a significant challenge in industry. This can be explained as being due to the increasing need to deal with much wider ranges of materials. Also, an important characteristic is the capability of such systems to machine three dimensional features and processes with no material constraints, which further differentiates the micro-manufacturing system from the typical MEMS and LIGA systems (Vogler, 2002). Also, in order to deal with a wide range of materials, dimensions and manufacturing processes within a micro scale, scaling down the processes and tools is required to meet the needs of achieving more machining efficiency and productivity.

Furthermore, defining machining accuracy is another challenging aspect in miniaturising manufacturing systems, as maintaining the required level of accuracy is a significant factor in determining the performance of the machine. Also, geometric errors need to be accurately identified and effectively compensated in order to improve the part feature accuracy (Lu et al, 1999). Figure 1.3 highlights the boundaries of the design process in this research, which focuses on designing a miniaturised machining cell that is capable of performing a micromachining level of accuracy.

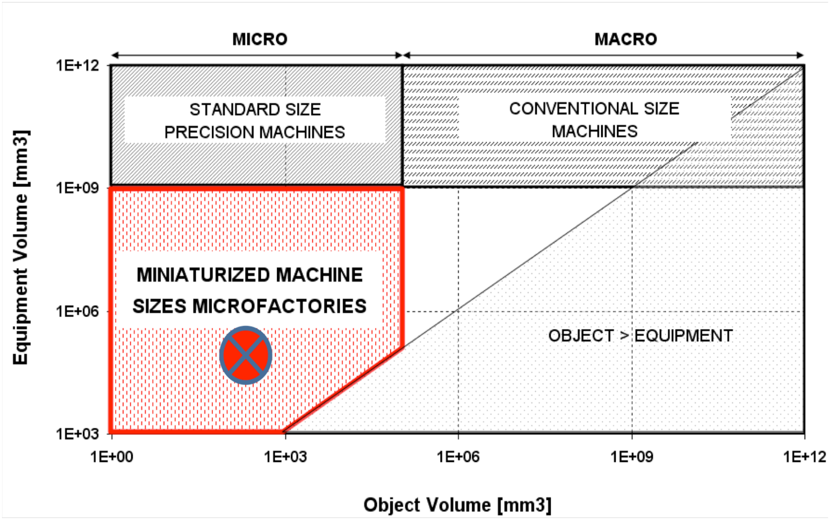


Figure 1.3: Targeted machine size and accuracy level.

This level of machining accuracy is sufficient to deal with components with dimensions up to 100 mm³ as it provides an accuracy level of 0.01% of the components dimensions (fig 1.4).

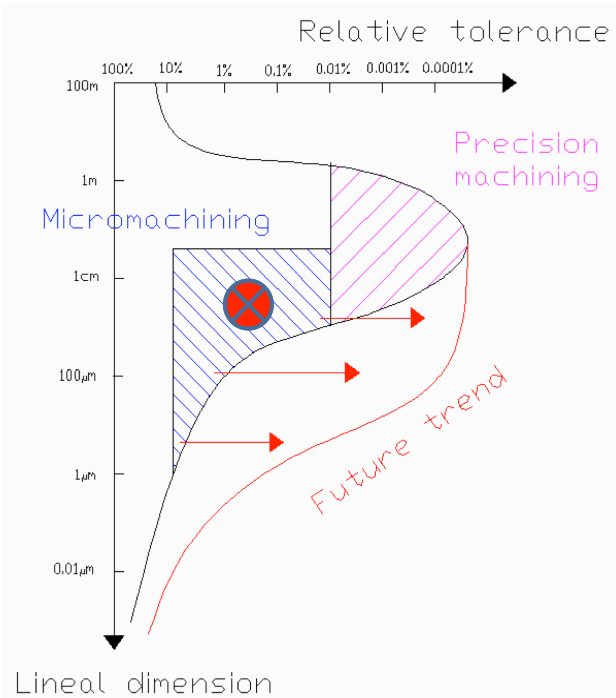


Figure 1.4: Targeted machined components size and accuracy level.

These specifications of machine size, machined component size and accuracy level can be used as guideline in the development of the novel design in this research.

Furthermore, manufacture of micro products in general is not restricted to specific materials and processes. Also, this can be linked to the ability of these systems to perform three-dimensional processes using a wide range of components and tools. In product development, principles and methodologies for design of micro products take into account functionality as well as manufacturability as the key area of interest.

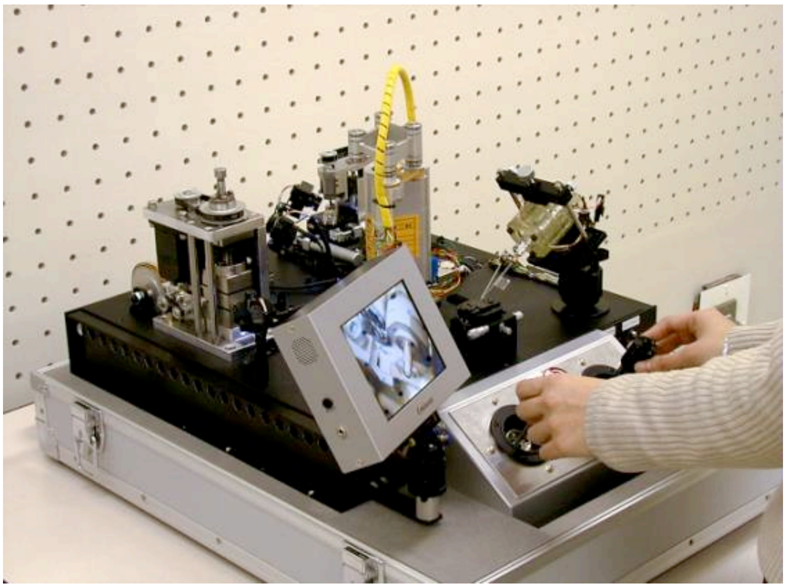


Figure 1.5: A miniaturised desktop machine (Okazaki, 2002).

Fig. 1.5 shows a previous work of the Mechanical Engineering Laboratory (MEL) in Japan of a miniaturised desktop machine that is capable of achieving a size reduction of 1/10 of a production machine, and 1/100 of energy consumption of a conventional factory.

Many small-size products have successfully been developed as prototypes in research labs by use of expensive techniques, mostly suitable for prototyping, but most of the time their mass production is delayed due to the difficulty in developing a cost-effective manufacturing process with reasonably low variability. In fact, developing a micro-sized product is not only a matter of downscaling a macro product and process, but it is a question of a different way of thinking using different principles and methodologies (Kussul et al, 2002).

1.4 Research Aim and Objectives

Unlike many micro-manufacturing systems in the market today, such as multi-axis desktop machines that focus on performing only one manufacturing process at a time, a new architecture can perhaps include more than one process being performed at the same time. In addition, a new architecture can also be reconfigurable and thus able to switch between processes easily, and perhaps automatically. Such a composite micro-manufacturing machine is the concern of this research.

The aim of this research is the development of a modular and reconfigurable micro-manufacturing cell but without compromising on the level of precision achievable. Additionally, such a machine should be compact enough and capable of processing concurrently a variety of part within a strict overall volume. This can envisage a number of real world applications for such a machine tool and in particular, applications that involve the rapid manufacturing of parts at the point of use. Examples are many and include healthcare, military, electronics as well as maintenance applications in aerospace or 'big science' instrumentation.

However, this is a challenging goal as it demands the progress of state of the art and therefore a complete rethink that is beyond traditional machine design approaches and indeed conventional machine designs. Therefore, this research is concerned with addressing the following key questions:

1. How can we compact several processes in a strict volume to reduce overall footprint as well as energy requirements for processing parts within an overall volume of 100 mm^3 but at the same time the overall machine tool can be rapidly reconfigured as demand for parts changes?
2. What kind of machine frame design would ensure concurrent processes to take place, rapid reconfiguration but not compromise on the precision requirements for micromachining and be able to achieve high production throughputs?
3. What kind of design can ensure modularity such that it can either function as an isolated stand alone manufacturing cell or combined with other similar cells into a microfactory?
4. How much machining precision can be achieved with a design that satisfies those requirements?

These questions clearly challenge the current convention and even partial progress in addressing them can potentially progress the state of the art. From a practical perspective, meeting those requirements is a compelling case especially for high value manufacturing. To address those questions this research has proceeded with the following objectives:

1. Review the current state of the art in reconfigurable machine tool design.
2. Explore alternative micro machine tool designs that can potentially meet those requirements and assess their mechanical performance by means of the complete computer aided engineering workflow including concept drawings, CAD and Finite Element Analysis.
3. Develop and test a physical prototype by means of static as well as dynamic analysis.
4. Develop an FEA model of the novel design that accurately represents the prototype and conduct a simulation-based study to determine how the mechanical performance and projected precision of the machine tool can be optimised.

1.5 Thesis Structure

This research consists of eight main chapters. Each chapter will provide significant information on the development of this project throughout each stage.

As described earlier, a background of the research, including definitions and information of manufacturing was introduced, including overviews, development over time and statistical information of the financial aspects of the field of manufacturing. Also, an aim and objectives were presented, providing a guideline and justification of this research, as well as stating the challenges and scope of this project. The next section presents a review of the state of the art of micro-manufacturing, highlighting the concept, techniques and current research interests in micro-manufacturing over the past few years. Moreover, this section will underline the current boundaries and capabilities of RMS by reviewing some of the current applications and projects in industry.

Then, framework and research methodologies are stated in the third chapter, aiming at showing the used approach in initiating and developing the proposed conceptual novel design and prototype in this project. The fourth chapter will review the development of the conceptual design in this project. This includes providing an overview of the design requirements, specifications, and used design tools and approach as well as providing a step-by-step work progress report. Chapter five will provide an overview of the prototyping process in this project, starting with the project management tools and considerations, material selection and justification as well as mechanical and electrical components. Then, the sixth chapter will offer a comprehensive assessment of the proposed conceptual design from the previous chapter, aiming at providing a scientific justification of designing the micro-manufacturing system. Also, it draws attention to the level of performance and robustness of the design prior to the prototyping stage. A seventh chapter will include an approach to optimise the current design and prototype by stating optimising methodology and assessment process. Finally, the last chapter aims at drawing conclusions resulting from this research project. Recommendations are also made for future work, providing solutions to improve the proposed design.

Chapter 2:
Literature Review

Chapter 2 - Literature Review

2.1 Introduction

This section will focus on reviewing the Reconfigurable Manufacturing systems (RMS) concept, relating to its involvement in developing the proposed design and prototype in this project. Overall, this chapter presents a background of micro-manufacturing and Reconfigurable Manufacturing Systems (RMS), highlighting their applications, limitations and significance to the industry. However, in order to design such a system, key features from several manufacturing strategies, such as Point Of Use manufacturing (POU), Cellular Manufacturing (CM), Manufacturing Process Planning (MPP) and Scalable Manufacturing, must be implemented as part of the development process of the novel design. The implementation of these strategies will be validated within the following section by providing an overview of implementation challenges and industrial applications of all these concepts in industry and within this research.

The growing significance of micro-manufacturing is due to the rise in global market demands for supplying cost effective and high quality products and services. Micro-manufacturing is one of the essential new technologies in industry, and this importance can be emphasized whilst acknowledging the location as well as the duration of manufacturing the products. The advantages of micro-manufacturing extend toward other aspects, including smoother mobility, enhancing productivity, lessening the capital investment required, sustaining a competitive advantage and minimising costs regarding energy and space (Mehrabi et al, 2000).

In manufacturing, the market trend is clearly putting pressure on the concept of mass production, as micro products' mass customisation is becoming increasingly more favoured. This increase is evident as micro product designers are continuously introducing new elements in their micro products in order to keep up with the growing demands of customers (Wiendahl et al, 2004). Manufacturers are required to sustain a flexible response to demand as the global market becomes more competitive. This flexibility in response can be obtained through higher volume regarding production, micro-manufacturing based on an industrial scale and maintaining low cost operations. Therefore, micro technologies can be considered as greatly efficient when used with products that denote high accuracies and three-dimensional geometry in non-silicon resources.

2.2 Micro-manufacturing: Drivers and Market Growth

The increasing demand for micro products and components within industry is driven by the potential and capabilities of newly developed systems including micro-manufacturing systems. Due to this factor, the market has been greatly increasing throughout the past decade, showing a significant growth between 2000 and 2005 reaching 60 billion USD from 30 billion USD in 2000 (Mounier, 2005). Based on an early adoption of micro-manufacturing, there are significant possible economic benefits in moving towards the micro-factory paradigm. This includes implementing new applications in industry, leveraging the advantages of micro-manufacturing, such as low production costs, small-size systems, low weight and power consumption and increased production flexibility and multi-functionality. Moreover, it has been estimated that the micro machine tools market in Japan is capable of reaching $1.1 billion in 2015 and similar market growth is expected for the U.S, driven by the rapid expansion of the biomedical industry able to perform at 16% per year.

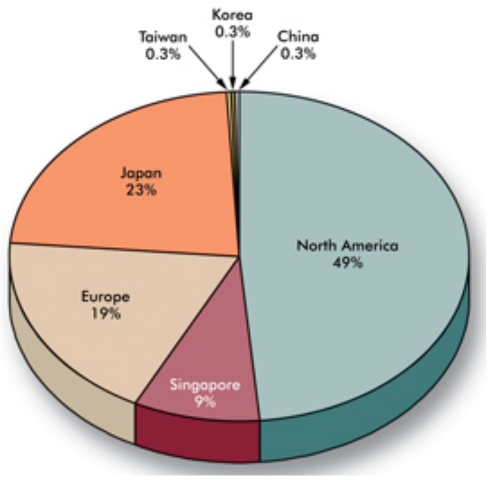


Figure 2.1: Revenue-based global micro-manufacturing market share 2010.

Moreover, market research analysis reports by several parties, including Yole development and European Microsystems Association, indicated that the market of micro-manufacturing is expected to increase progressively within the next few years due to the increased interest of manufacturers to cope with the demand. Overall, the global market share can be categorised based on the total revenue of each market. The market share is divided between North America, Asia and Europe. In fact, in 2010, the North American market generated an estimation of 49% of the total revenue globally while Europe came third with 19%, following Asia 33%, Japan 23%, Singapore 9% leaving Taiwan, Korea and China with 3% each, as seen in figure 2.1.

2.3 Reconfigurable Micro-Manufacturing Systems (RMS)

2.3.1 Background

The need for developing micro-factories became apparent when production of small-machined parts using conventional machine tools became too costly and inefficient. This does not apply to speeding up and slowing down machines. Rather, it refers to rapid modifications in system and machine structures through the addition and removal of productive equipment modules. In the future, the introduction of scalable and adaptable systems will change the way capacity decisions are approached by eliminating attempts to forecast economic conditions and by allowing quicker responses to market and demand fluctuations within minimal time. Also, the required space and energy to produce micro-scale parts affects the production cost of each part, making it very unlikely that better production/cost utilisation can be achieved (Abramovich, 2005).

Therefore, it was necessary to develop platforms that are suitable for producing small-size components with high precision and accuracy using flexible desktop machines. This idea, which was developed during the 1990s, had several advantages, such as better use of resources, including time, energy and space (Okazaki, 2004). This approach requires future manufacturing systems technology to meet certain objectives which go beyond those of mass, lean, and flexible manufacturing. These objectives include reducing lead-time (including ramp-up time) for launching new manufacturing systems and reconfiguring existing systems whilst also rapidly upgrading and quickly integrating new process technology and new functionality into existing systems.

2.3.2 Characteristics of Reconfigurable Micro-manufacturing Systems

Micro-manufacturing systems can be made in different designs and used in a number of applications. However, there are certain common characteristics that must be satisfied in each system. These characters represent key requirements that must be taken into consideration before designing and producing any (micro-factory) unit, as micro-factories are expected to become widely accepted and used in industry more than before. This is due to the comparison of its advantages and characteristics to any other production methods and techniques. The first issue is based on benefiting from the advantages and capabilities of conventional machine tools by scaling down their manufacturing processes as - unlike MEMS - they provide the capability of machining a wide range of material and sizes. Also, this approach aims at avoiding insufficient use of resources, as conventional machine tools have a relatively large size compared to the produced components (Hansen and Eriksson, 2005). Another requirement of designing such a platform is the ability to perform assembly operations including material transfer, which requires a high precision in order to be performed efficiently (Trevisan, 2006).

Since the design and characteristics of manufacturing systems have been affected by the changes in market demand, resulting in rapidly modified process technologies and policies, a number of manufacturing and production strategies have been introduced, aimed at increasing productivity and achieving better response times for the market (Abdi et al, 2003). These strategies include Dedicated Manufacturing Systems (DMS) and Flexible Manufacturing Systems (FMSs), which have managed to fulfil some of the market demand on an operational level. Nevertheless, the gap between supply and demand has increased due to the limited adaptability of these systems. This requires further improvement within a process level that involves the strategy of performing machining processes and machine design.

In order to solve these issues, a new approach to the design of machine tools had to be introduced, aimed at increasing the flexibility and responsiveness of these systems in order to cope with the rapidly increased demands in volume, specification and type. The concept of Reconfigurable Manufacturing Systems (RMS) has been developed through the last few years to consider the possibility of offering more than one process or function that can be undertaken using a micro-factory unit (Koren et al, 1999). In order to give potential to the advantages of this concept, a comparison has been conducted by Koren (2005), which shows the differences between the three types. Table 2-1 compares reconfigurable manufacturing systems to dedicated and fixed systems, highlighting key advantages such as adjustable machine structure, customisation and flexibility when needed. RMSs offer the ability to perform simultaneous machining processes to produce a wide range of machined parts, unlike DMSs, which can machine several yet identical parts and FMSs, which aim at performing several machining processes on specific part families. Furthermore, the characteristics in the table below define key requirements for designing RMSs, including having an adjustable structure for machine tools and systems, allowing rapid adjustment in production capacity and functionality by accommodating a wide range of machine processes and layouts. Meanwhile, including a scalable design and customised-level of flexibility provides the capability to deal with any part family.

Table 2.1 - Characteristics of DMSs, FMSs and RMSs (Koren, 2005)

	DMSs	**FMSs**	**RMSs**
System structure	Fixed	Adjustable	Adjustable
Machine structure	Fixed	Fixed	Adjustable
Flexibility	No	General	Customised
Scalability	No	Yes	Yes
Simultaneous machining operations	Yes	No	Yes
Cost	Low	High	Intermediate

Furthermore, since manufacturing systems usually face changes in functions and production methods, it was necessary to develop the current concept of the micro-factory to respond to such changes by allowing reconfigurable micro-factory platforms and modules that could be assembled to perform more than one functionality and production capacity (Ashida, 2000). Therefore, process integration of the platform should satisfy the main concept of being a reconfigurable platform by developing sub-systems that are responsible for handling components between the different processing modules. Such a system should be designed based on the speed required and the need for simplicity.

These recent developments in RMS design can provide a wider range of products that can be produced by only one platform. It is also cost effective since fewer resources will be consumed during each process and RMSs can deliver high throughput and high flexibility, while avoiding high investment costs as shown in (fig 2.2). Compared to other machine tool design approaches, RMS aims at reducing design lead-time and machine set-up time. These new systems provide precisely the functionality that is needed; exactly when it is needed (Heisel, 2006). This approach requires designing a system with a high level of parts integration and modularity, which means that any part within the system has to be capable of quickly adapting to different production requirements as well as being capable of integrating with other parts to increase the level of machining flexibility within the system.

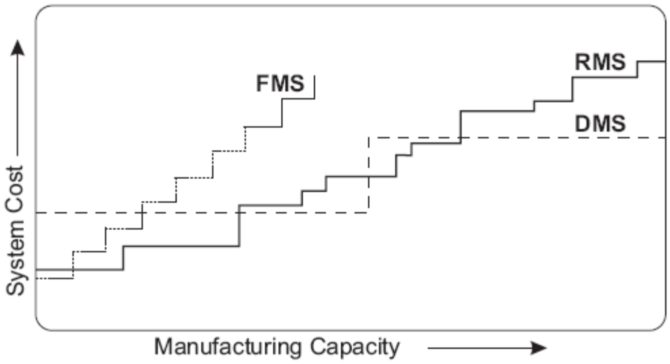


Figure 2.2: Comparison of DMS, FMS and RMS costs over production capacity (Koren et al, 1999)

Figure 2.3 illustrates a roadmap showing how market demand and technology trends have led to the need for reconfigurable manufacturing systems (RMSs) and machine tools (RMTs).

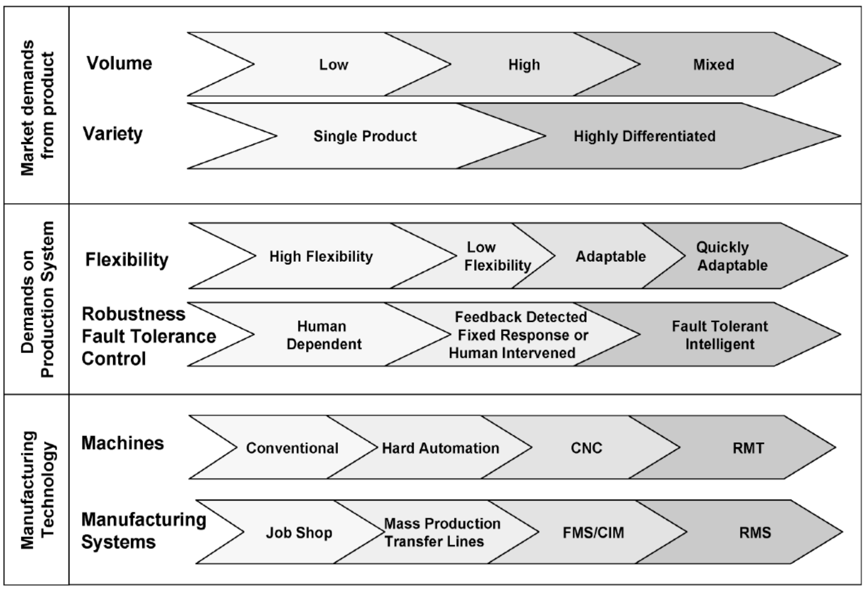


Figure 2.3: Evolution of manufacturing towards RMSs (Molina, 2005).

Today's manufacturers need to cope with demand by supplying unpredicted volumes of highly differentiated families of parts. This sort of demand requires a faster response from production systems using reconfigurable machine tools and manufacturing systems as it deals with changes in part specifications and volumes. Based on these changes in demand, the flexibility of production systems has been developed from having highly flexible systems designed to deal with limited numbers of part family to be quickly adaptable, as these systems are required to satisfy a wider range of product families. These developments in market and production demand are considered as drivers to introduce new machine tools and manufacturing systems, as these technologies deliver a key feature represented in their ability to be reconfigured. Also, the introduction of RMS has benefited industry by increasing the amount of product varieties over time. Traditional RMSs such as Dedicated Manufacturing Lines (DMLs) cannot adapt to market fluctuations whereas conventional RMSs such as CMSs and FMSs can proportionally adapt to demand variations (Fig. 2.4). However, their adaptation is not quite enough for dynamically increasing demand variations. In order to fulfil the gap between dynamic market demands and the capacity and functionality of manufacturing systems, a reconfiguration strategy is necessary to focus on grouping products into families before manufacturing, based on process similarities (Abdi, 2003).

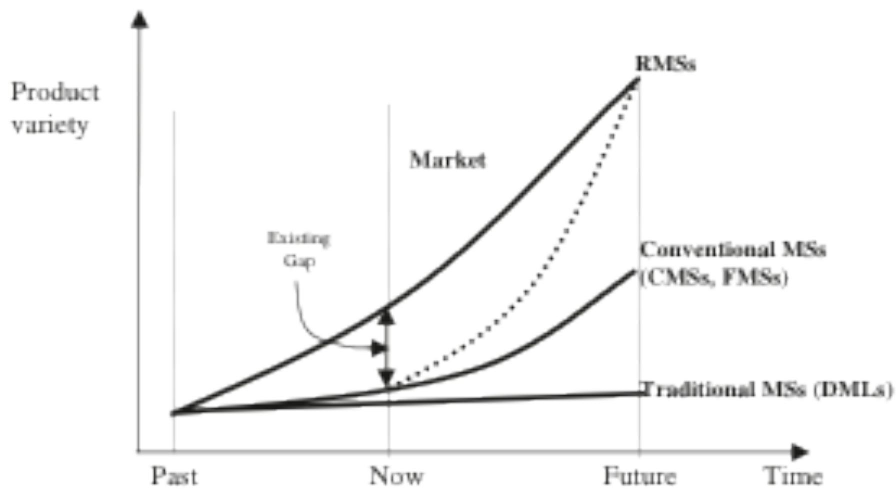


Figure 2.4: Effects of market changes on RMSs over time (Abdi, 2003).

In general, an RMS is made up of various modules with changeable factories. This process of reconfiguration can involve replacing some of the existing modules with another in order to make the entire production system more suitable to accommodate and process a wider range of products, indicating that RMTs will face several challenges in accommodating several ranges in size, type and machine tools (Moon et al, 1999).

As shown in fig. 2.5, the introduction of RMSs has significantly improved the quantity and range of machined parts as well as the cycle time of these parts. However, the increased use of shared components has also raised the assembly costs, but the savings on material outweigh the expenses on assembly. The accretions in output and the number of variants combine with the shortened cycle time which leads to convincing proof of the predicted benefits of re-configurability (Heisel et al, 2004).

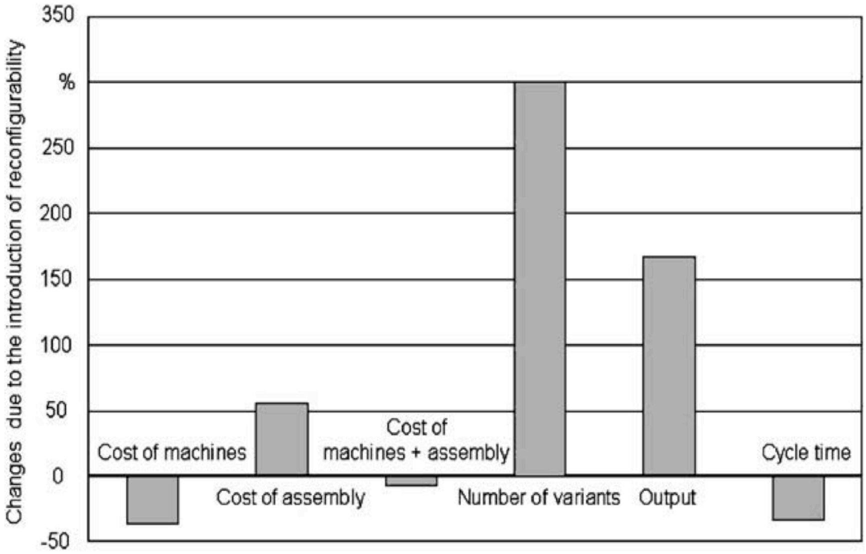


Figure 2.5: Benefits of introducing reconfigurability in industry (Heisel et al, 2004).

Based on the method similarities required to process products, sorting product families into groups before starting the production process will minimise the gap between rapid changes in market demand and the capacity and functionality of manufacturing systems (Abdi et al, 2003). In this case, the production process within a reconfigurable production line will begin by evaluating the requirement of the entire production process in order to select the appropriate production plan including categorising product families, which can be manufactured in the RMS. This will be based on achieving a smooth production process. Following that, a manufacturing strategy can be developed dependant on analysing the requirements and the capabilities of the production line in addition to maintaining a detailed understanding of company’s products and market, which is essential (Koren et al, 1999).

The process of developing, as well as designing the product, executes an RMS design stage of product-process to ease the progress of modularity integration. Therefore, the reconfiguration process of any machine tool can be determined according to the need for reconfigurations based on product variety (Fig. 2.6) (Xiaobo et al, 2001). The reconfiguration process varies from having multi-product machine tools to dedicated single-product production machines.

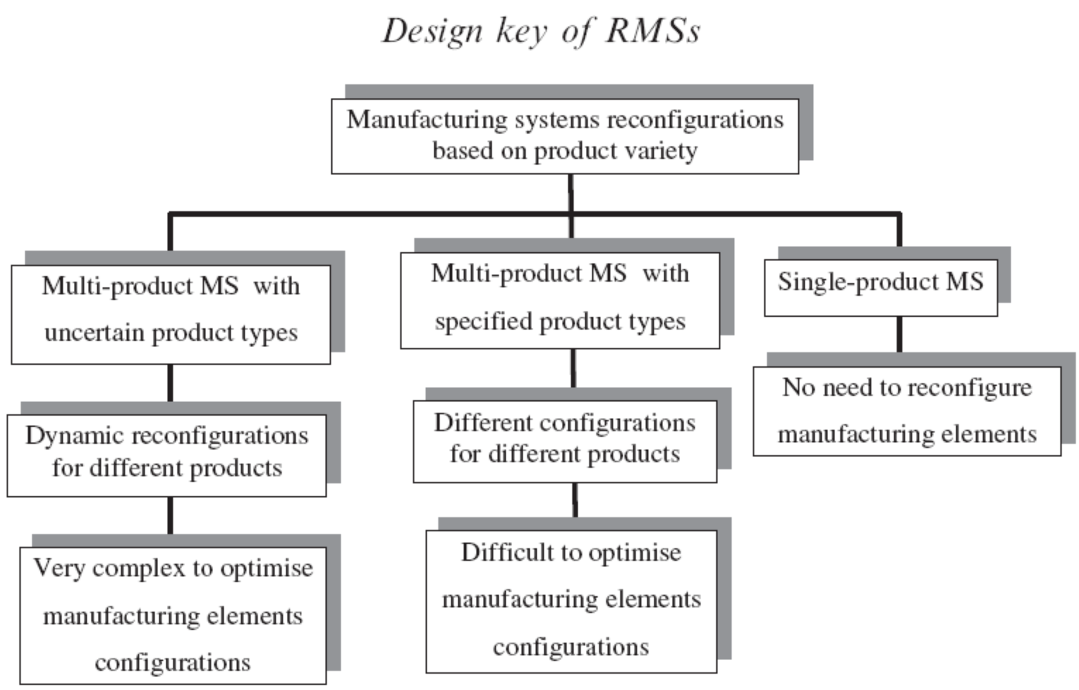


Figure 2.6: Design process of RMS (Xiaobo et al, 2001).

The relationship between RMS and market demand can be highlighted as the main approach when designing any RMS in industry (Fig. 2.7). Therefore, this strategy is focused on creating a reconfiguration link between both sides of the process. In order to achieve that, product types are first selected based on market demands and available technology within the RMS.

The selected products for the production range are then transferred to the product design stage in order to be designed (or reconfigured) based on modular structures. Whereby, different combinations of individual modules are achieved to assist the production of different products with the same available resources. Following this, the product design stage facilitates the integration of modularity through the product-process design stage of the RMS. As a result, a modular structure in both product and process design will facilitate the reconfiguration of manufacturing elements in order to rapidly achieve variant modular configurations according to module instances of products in the production range. The modular structure improves the adaptation to any future requirements for changes in the product design and processing needs through easy upgrading of hardware and software instead of the replacement of manufacturing facilities.

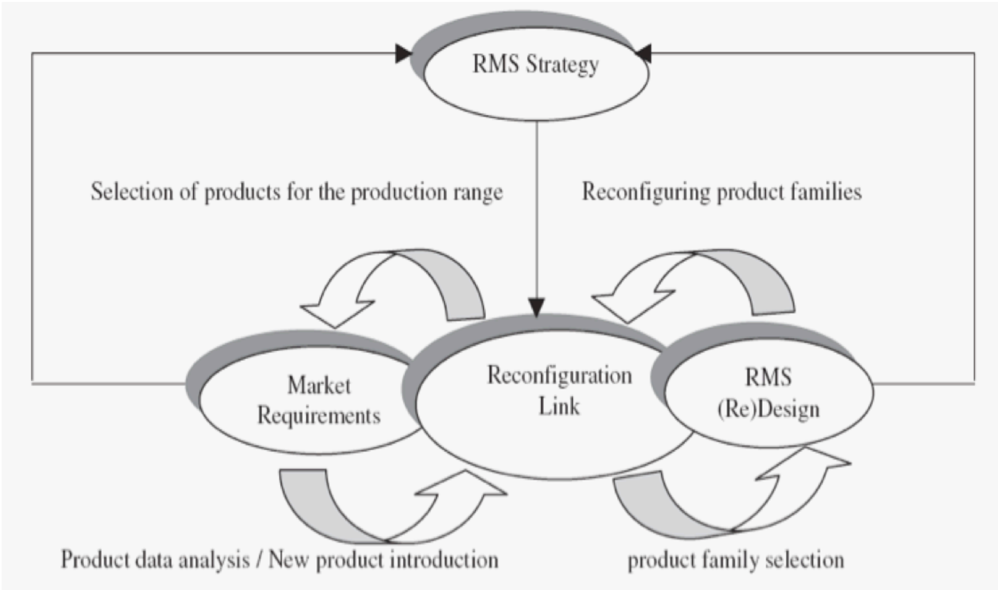


Figure 2.7: Link between market demand and RMS (Heisel et al, 2004).

In addition to this, part of the reconfiguration process is to develop a connection between RMS design strategy and tactical design while using the process requirements as the basis of product classification, thus creating a number of product families. A product family is a group of products with familiar technology at its core that tackles correlated market applications grouping (Meyer et al, 1995). According to Rampersad (1994), the product family contains a product variations group with characteristics that are very much alike.

Identifying product families within process planning is based on process sequencing and overall routing where same groups of facilities are shared among product family members. A group of parallel products with identical functions can be identified as a product family according to Stadzizsc and Henrioud (1995). Based on that, these products are sharing similar features but with different variations. These variations are caused by the secondary tasks, the products appearance or the additional components, which are options to be added to the product.

Figure 2.8 shows an example of developing a reconfiguration link between a RMS and market demand based on creating product arrangements, families and types. The process of initiating a design strategy of RMS starts by analysing the market demand in order to categorise products into groups. Based on the required production process and parts similarities, product groups will be defined creating a range of product families, where each family has similar properties and requires a specified production process. The hatched line is used to present the task of modelling product family selection using an Analytical Hierarchical Process (AHP) and is then used while considering both market and manufacturing requirements. The AHP model is verified in an industrial case study through using Expert Choice software. The solutions take advantage of monitoring sensitivity analysis while changing the priorities of manufacturing and/or market criteria.

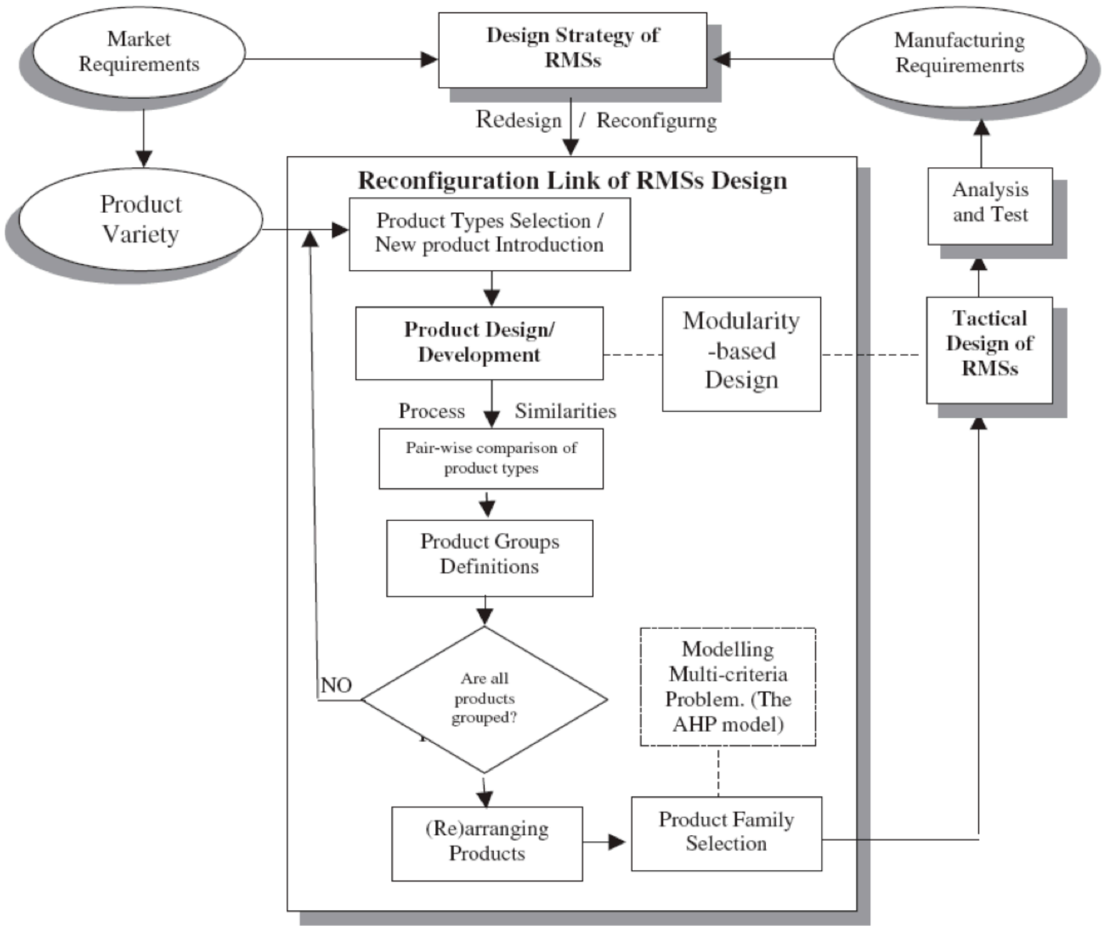


Figure 2.8: Design loop and re-configuration link of RMSs (Heisel et al, 2004).

After reviewing design aspects and characteristics of RMS, and highlighting some of its key advantages over conventional machine tools and systems, it is important to discuss the implementation of some key manufacturing strategies and techniques that can add more value to the novel design. These strategies include Point Of Use manufacturing (POU), Cellular Manufacturing (CM), Manufacturing Process Planning (MPP) and Scalability of RMS. To deliver a full understanding of each strategy, it is important to provide an overview and analysis of each strategy in order to justify the selection of these strategies in this research.

2.4 Manufacturing Strategies

2.4.1 Scalability of RMS

Modular machine tools have been on the market for several years and in order to develop a novel design for an RMS, it is important to consider manufacturing strategies and machine tool designs that help to add more value to the novel design.

Scalability is a key characteristic found in reconfigurable manufacturing systems. Scalable systems can be defined as systems that satisfy changing capacity requirements efficiently through system reconfiguration (Spicer et al, 2005). This is also known as expansion flexibility. Also, Koren et al (1998) defined it as ‘the ability to adjust the production capacity of a system through system reconfiguration with minimal cost, in minimal time, over a large capacity range, at given capacity increments’. The development of a scalable RMS requires achievement of a high level of modularity and flexibility within any RMT/ RMS since it is based on the system’s capability of efficiently adapting to changes in capacity requirements through system reconfiguration by applying rapid modifications in system and machine structures through the addition and removal of productive equipment modules.

In order to illustrate the advantages of implementing a scalable RMS over some of the conventional machine tools, the capabilities of each category must be evaluated based on criteria including capacity increment size, lead-time, cost per unit of capacity and floor space per unit of capacity (Spicer et al, 2005). In addition to this, the evaluation process will include four types of machine tools that are used in high-volume production.

Table 2.2 - Conventional Machine Tool Evaluation (Spicer et al, 2005)

Machine type	Capacity increment	Lead time	Cost per unit of capacity	Floor space per unit of capacity
Single-spindle CNC	Small	Small	Large	Large
Transfer machine	Large	Large	Small	Small
Head changer	Medium	Medium	Medium	Medium
Multi-spindle CNC	Medium	Small	Medium	Medium

Table 2-2 provides a comparison between four types of machine tools and systems based on their response to changes in demand and scalability. The first type represents a machine with a single-spindle CNC, which requires a short lead-time to be purchased and installed due to the standardisation of CNC machine tools in industry. However, since most CNC machines require at least three degrees-of-freedom to machine parts, the floor space required to accommodate three actuators (motors) for each spindle is considered large compared to the size of the actual machine, which also increases the cost per unit. On the other hand, a pick-and-place material transfer machine provides significantly less flexibility than a CNC machine, as it is only capable of dealing with a single part at a time. However, each transfer station has one motion unit, which means it requires little floor space and low cost per unit.

Since each transfer machine consists of an array of transfer stations, the required lead-time to install these stations is considerably long. The third option in this comparison is a head changer based on a multi-axes CNC machining centre using multi-spindle drill heads instead of a single-spindle for cutting, while the fourth option is a multi-spindle CNC where each spindle has automatic tool change capability, which aims to increase the way each spindle is being used within the machine in a more efficient way. Both options are similar when comparing floor space and cost per unit. However, the fourth type requires shorter lead-time for purchasing and installation since it is based on standardised CNC spindles as in option one.

When comparing all four machine tool options, all of them showed limited flexibility in a specific area or functionality, which indicates that none of the above options are truly scalable to cope with changes in demand. Therefore, the scalability of a machine tool must be addressed and considered during the design stage of any RMS using the same evaluation criteria mentioned earlier.

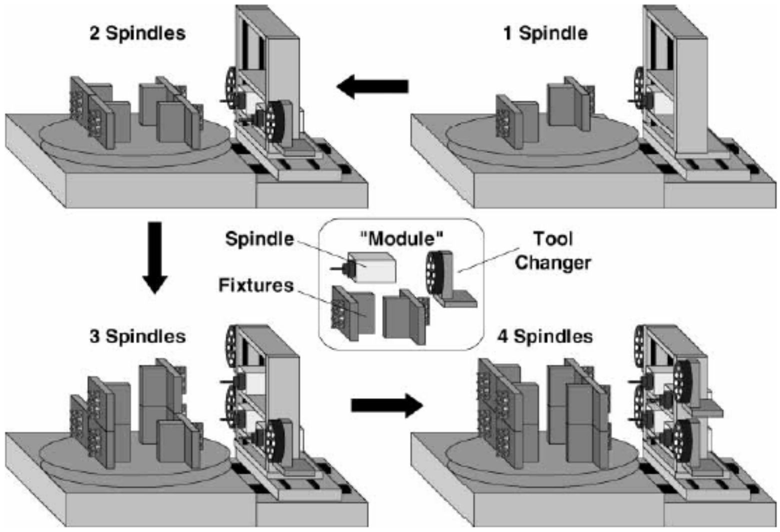


Figure 2.9: Example of a scalable multi-spindle CNC machine (Spicer et al, 2002).

An example of a scalable RMS is shown in fig. 2.9, which aims at providing four states of production capacity by reconfiguring the machine layout, number of spindles used and fixture parts. The modular design of the machine tool provided a level of flexibility that is capable of adapting to changes in demand within a short time. Overall, the result of implementing a scalable design for a CNC machine indicates an improvement in performance and functionality by having a small-capacity increment as a single spindle, while performing as a multi-spindle CNC machine with consideration to cost and floor space per unit of capacity, as shown in table 2-3.

Table 2.3 - Scalable Machine Tool Evaluation (Spicer et al, 2002).

Machine type	Capacity increment	Lead time	Cost per unit of capacity	Floor space per unit of capacity
SMS-CNC	Small	Small	Medium	Medium
SL-Transfer	Medium	Medium	Small	Small

Based on the evaluation of machine tool scalability, which shows the advantages of scalable design, it is crucial to include such a design strategy and feature when developing a novel RMS in this research. Therefore, issues such as lead-time, capacity and floor space will be considered before designing and during the selection stage of material and mechanical components. This suggests a small footprint machine with standard machine tool heads.

2.4.2 Point Of Use Manufacturing (POU)

Opportunities can be observed within several industries such as engineering and medicine by introducing new manufacturing strategies such as Point Of Use (POU). This strategy aims at delivering goods and services at the "Point Of Use" (POU) in a timely and economic fashion. Such a concept is potentially capable of driving micro-manufacturing from being a centralised manufacturing model to a more distributed manufacturing model that coexists with the centralised model by moving the production/machining unit to the location where the machine parts (products) will be used (Ehmann, 2007).

While many research challenges will need to be considered, it is clear that micro-manufacturing methods, among others, have the potential to satisfy any number of the applications in the POU domain. These challenges can have technological, environmental or socio-economic characteristics when a POU manufacturing strategy is implemented. For example, developing miniaturised production machines and their key component technologies that are required for processing, storage, handling, and transportation of material across the desktop- or micro-factory, offers a set of technological challenges. The impact of implementing this concept can be significant to the environment due to the reduction in energy costs, pollution, and waste associated with smaller-scale parts and the smaller machines that make them.

A number of aspects can be considered in POU miniaturised and desktop manufacturing systems, such as being an inexpensive, easily deployed and an on-site solution for several applications. Fig. 2.10 shows a micro-milling machine tool by Ingersoll. This machine was designed using a machining centre based on providing a high accuracy milling process on location. Notably, high customisation, production output and machine tool reconfigurability are key factors in implementing this strategy (Koren et al, 1999). The skills needed to operate manufacturing systems decrease with progressing automation. Therefore, the production of low value parts shifts to low wage countries, representing a significant socio-economic impact.

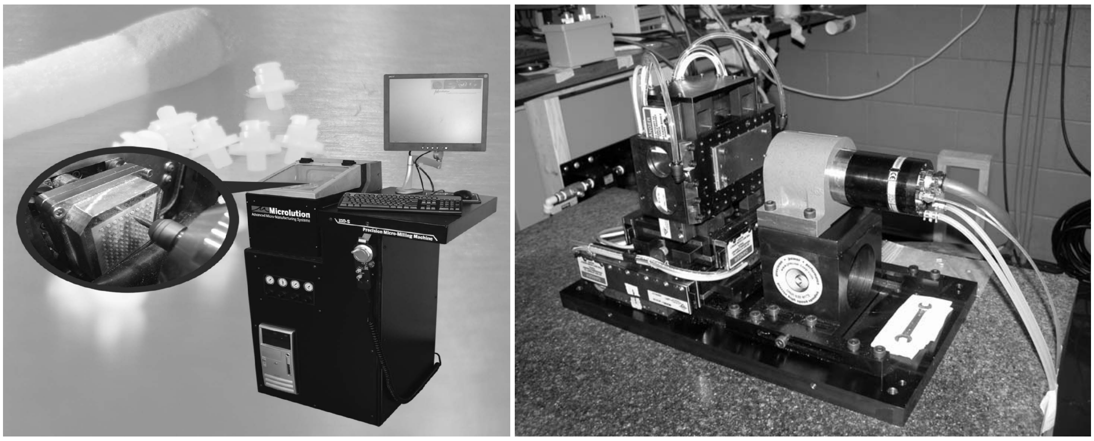


Figure 2.10: Ingersoll Machine Tools and Machining Centre (Ehmann, 2007).

One area of application is consumer product manufacturing, which is based on a combination of two main categories. First, there are the main components that represent the core of the product that any product cannot function without. Then, there are secondary components that distinguish each product from the other within the same product family. Usually, the first category is always available to speed into the production process due to its importance. While, on the other hand, the second type is available due to the high volume of production considering its standardised features and high compatibility across wide ranges of products. Based on this strategy, it is clearly shown that the assembly process of the two categories is the main step within the production line. Therefore, in order to increase the efficiency of the production line and to achieve a more economic way to produce the different variants, one method can use the same semi-finished parts and apply final product finishing and inspection of production within the same production line. This stage may include adding some of the common machining processes to the assembly line, such as visual inspection, drilling or milling to apply the required changes. Including these processes inside an assembly line becomes conceivable as assembly lines are modular, convertible, and customisable to a very high degree.

Methods from reconfigurable manufacturing systems are necessary to achieve this objective. Although there are few examples of reconfigurable manufacturing systems (RMS), experience from industrial production shows the benefits. The increased use of shared components also raises the assembly costs; however, this results in achieving savings on material, which outweighs the expenses on assembly. The increased output and the number of variants combine with the shortened cycle time to offer convincing proof of the predicted benefits of re-configurability (Heisel et al, 2006).

Figure 2.11: Mobile manufacturing unit with peripherals (Heisel et al, 2006).

Another area of application is healthcare, where this strategy is known as Point Of Care (POC). The introduction of POC within several healthcare fields including dental, biomedical and general testing aims at providing a wide range of manufacturing processes, such as batch production and customisation of medical components at the POC (Myers, et al, 2005).

Implementing Point Of Use (POU) is considered a key feature during the design stage of the novel RMS in this research, which highlights some of the design requirements and functionalities of the RMS. Based on the above review, designing a novel RMS that can deliver POU manufacture requires a small footprint machine that can satisfy a number of applications, such as assembly, inspection and small modification (machining) processes, while keeping in mind the previously mentioned technological and environmental challenges. Potential advantages of this approach include energy-efficiency, mobility and low operational cost (Sun et al, 2008).

2.4.3 Cellular Manufacturing (CM)

In industry, some demands can be met by traditional production line technologies, which are based on organising production machines in a serial arrangement dedicated to processing a single type of parts (Jeon, 2006). However, due to the need to increase the flexibility and responsiveness to customer demands, a new manufacturing strategy was introduced known as Cellular Manufacturing (CM) (Makatsoris et al, 1995). The concept of Cellular Manufacturing was introduced as a category within Group Technology (GT), which can be defined as the grouping of very similar concepts, principles and tasks in a single manufacturing process to increase productivity (Greene et al, 1983).

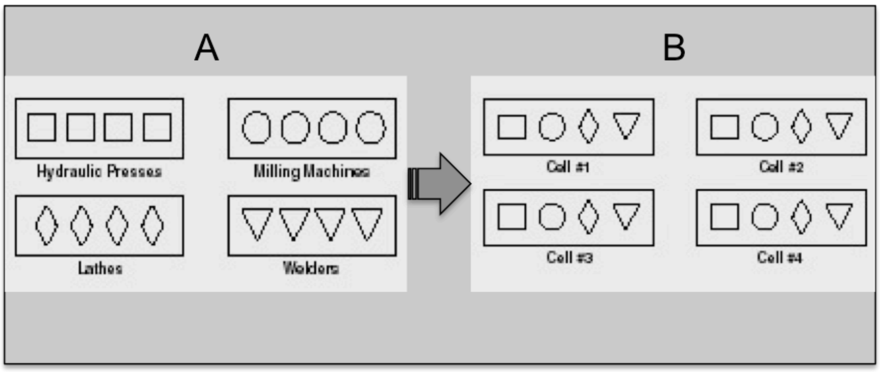


Figure 2.12: Process-based line and Cellular Production (Wemmerlov, 2004).

The above figure (Fig. 2.12) highlights the dissimilarity between the traditional production line (A), which focuses on allocating similar machines in order to perform a single process, and (B) where the cellular manufacturing concept is demonstrated by grouping a range of machining processes in machine cells where each cell is capable of performing several machining processes in order to produce a range of product families. Therefore, in order to perform more than one machining process on a component, category (A) requires moving this component from one station to another. On the other hand, the cellular layout in (B) provides the performing of all machining processes on the same component without the need to move the component to another station.

Product families are required to be configured as clusters in order to enable the processing of each family. The benefits of this approach are clearly shown in the higher utilisation of normal manufacturing as well as providing manufacturing systems with the ability to meet and adjust to the wide range of customers' demands at the same time

(Chen et al, 2004). One of RMSs requirements for aiding production management, the purchase of materials and products varieties production, is product clustering and grouping.

Implementing CM within a production plan can bring several advantages to improve the production process, which includes reducing material handling, set-up time and waste material (Wemmerlov, 1997). However, compared to production line technology, switching to CM can involve costly alignment of equipment caused by the replication of machines and cells within the micro factory. Also, a decrease in the shop floor flexibility is possible when implementing CM. This may occur when a change in demand affects the mix of machined parts within the cell, as some machines are limited to process specific part families (Makatsoris et al, 1995). Furthermore, this change can cause an imbalance in the cell's loading and capacity since some machine tools will be more utilised than others within each cell (Wemmerlov, 1989). Cell loading is a critical activity within any system, as it determines the overall balance of the manufacturing system. Nevertheless, these limitations can be minimised by implementing a performance assessment strategy where each aspect of the production process, such as the cell layout, mechanical components and machined part families are re-evaluated in order to maintain a satisfactory level of productivity (Al-Mubarak et al, 2003).

In this research, the principle of CM strategy can be implemented as part of developing a Reconfigurable Micro-manufacturing Cell. The aim of implementing such a strategy is to benefit the RMC by introducing certain advantages and characteristics of CM to the proposed RMC design. These characteristics include the ability of CM to be arranged to produce a wide range of products with efficient flow and high production rate and minimal material handling, which is highly suitable for a small size micro machining platform. Furthermore, implementing such a strategy requires understanding the characteristics of this strategy as these characteristics include number of cells, size, and number of machines, which can define the performance of the system. Based on this implementing CM in this project will influence the design, layout and process planning of the proposed RMC, as will be described at a later stage.

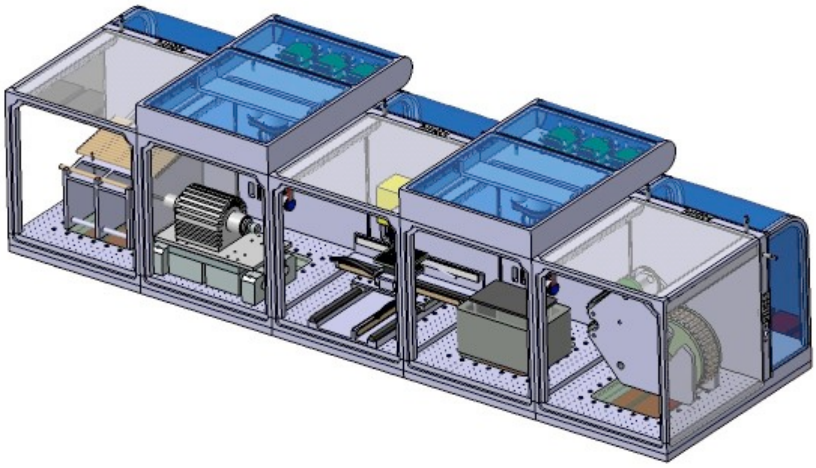


Figure 2.13: Cellular design for a micro-factory (Siltala et al, 2010).

A few years ago, a concept of Cellular Manufacturing was introduced to the micro-manufacturing field as shown in Fig 2.13. This cellular Microfactory, which has been developed by the Automated Manufacturing and Assembly Laboratory at the Tampere University of Technology in Finland, consists of a 1m long assembly line. Moreover, each module occupies a space 300mm x 200mm and 220mm high wide, and was sealed to ensure maximum cleanliness. Also, achieving a high level of flexibility in this Microfactory has been made possible by including a standardised software and hardware interface between modules. Each line of modules aims at producing loudspeaker assemblies for mobile phones, where each module is internally lit by arrays of LEDs (Siltala et al, 2010).

2.4.4 Manufacturing Process Planning (MPP)

Flexibility is usually regarded as the ability to match production to market demand in the face of uncertainty and variability (Iravani et al, 2005). Process flexibility is the result of being able to produce different types of products in the same manufacturing plant or on the same machine line at the same time (Sethi et al, 1990). Since process flexibility aims at producing multiple products to meet customised demands, which is essentially reflected by a personalised bill of material (BOM), it is important to consider the impact of the BOM constraints in order to generate an effective process plan (Muriel et al, 2006).

BOM can be defined as "items or raw materials that go into the product" (Garwood, 1988), and there are two types of BOM involved in manufacturing that have been widely implemented; traditional BOM, which can only be used with low-demand products when there is no pressure from competitors and modular BOM, a more flexible and contemporary BOM, which is required these days in order to cope with the demands of the market and the shorter life cycle of the products (Hua et al, 2008). Figure 2.14 shows the structure of each type of Bill-Of-Material. Considering the characteristics of any RMS, the tasks involved in identifying an optimally fit manufacturing configuration include the matching of activities and resources (Koren et al, 1999).

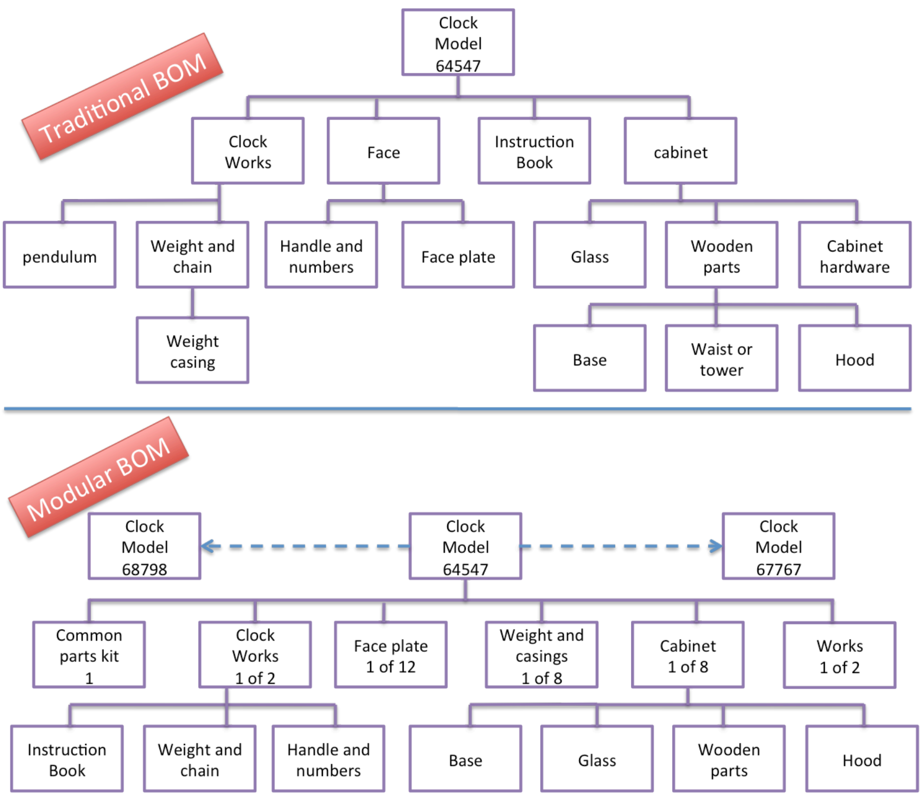


Figure 2.14: Examples of Traditional and Modular BOM shows required components to build a watch (Koren et al, 1999).

This process focuses on developing an optimisation approach that can be used to address issues that are critical in providing a high level of utilisation of activities and resources in a production line that produces multiple parts with reconfigurable flows. This strategy includes process selection, process sequencing and part load scheduling (Tang, 1997). In this research, the aim of implementing MPP is to help in identifying optimal manufacturing process plans in complex manufacturing activities. The implementation of the most advantageous manufacturing process plans is crucial in dynamic manufacturing environments since it ensures that optimal operating levels are attained.

2.5 Machine Tool Designs

As mentioned earlier, micro-manufacturing systems are deployed in many industries, which means it is important that these systems are able to cope with the demand of producing a wide range of high precision and small-scale components within each industry. Therefore, several machining and fabricating techniques need to be introduced as part of micro-manufacturing systems, aimed at delivering a high level of efficiency, productivity and quality (Son et al, 2008). In order to achieve this aim, most of the machining processes within micro-manufacturing are implemented based on miniaturising conventional machining processes such as turning, milling, drilling and grinding, which have already been well established. The advancement in machine tool technology, especially with the development of highly precise CNC machines, also helps to achieve very fine shapes with high accuracy. With regard to this, mechanical fabrication processes using solid tools are useful in terms of realising complex 3D features on a micro-scale (Rahman et al, 2004). If the applications of these conventional machining methods become available for the micro-manufacturing process, the production process for micro-parts will be advanced as an extension of the traditional material removal processes (Lu et al, 1999).

The following section will review some of the applications of machining and material handling processes within micro-manufacturing, which will give opportunity to implement some of these processes within the novel RMS in this research.

The following table (2-4) provides a summary of current capabilities of different machine tools. For example, the critical factor in micro milling (μmilling) is the tool material, which details its capabilities, while in micro wire electro-discharge machining (μWEDM), the whole wire tension and the guiding system are the most crucial. In micro sinking electro-discharge machining (μSEDM) the process is dependent on the electrode rigidity, spark gap and debris size. Alternatively, laser micro machining (μlaser) shows restrictions arising from the focusing angle of the beam and the laser spot. Finally, in micro electro-chemical machining (μECM) the electrode size is the most critical.

Table 2.4 - Comparison between several micro machine tools

	μmilling	μWEDM	μSEDM	μLASER	μECM	ECF
Maximum mould insert external dimensions (mm)	200x200x200	200x200x100	300x300x150	200x200x200	200x200x30	20x20x10
Maximum micro structured area (mm)	100 x 100	200 x 200	200 x 150	200 x 150	40 x 30	20 x 20
Minimum tool size (mm)	0,1	0,02-0,05	0,05	-	-	-
Minimum feature dimension (μm)	50 - 100	20-50	10 - 50	5	50	10
Accuracy (μm)	3-10	2	3	1	8	2
Aspect ratio	2-5	10-50	3-10	2-50	-	10
Roughness (μm Ra)	0,2	0,1	0,1	1	0,1	
Material removing rate (mm^3/min)	20	0,1	0,01	0,04	-	6×10^{-6}

Conventional size precision machine tools (fig. 2.15) have good machine characteristics, but the small size, complex geometry and high quality of micro products impose high demands on machine performance. This will increase the investment and operation costs and cause the manufacturing SMEs difficulties in accessing the technology, and thus the high value-added manufacturing business (Luo et al, 2000). Furthermore, these machines are generally very expensive, working in a tight temperature controlled environment, and they are inefficient in both energy and resource.

Figure 2.15: Conventional Machine tools (Qin, 2006)

The importance of miniaturising these conventional machines can be represented in a number of key advantages such as having smaller footprint and thus smaller space occupation and less energy consumption (Alting et al, 2003). Also, the miniaturisation can have an effect on the operational performance of these machines, as it increases machining accuracy due to the lower vibration amplitudes and uses smaller machining equipment (tool tips).

Starting with some of the common applications of micro machining tools, micro-mechanical machining methods are seen in mechanisms such as turning, drilling and micro-milling. These methods are considered a key process within micro machining, alongside clamping tools, micro grippers and accurate positioning devices. In the meantime, a new machining method is introduced as a result of developing a micro machine tool. The introduction of this new micro machine tool presents many benefits including environmentally responsible tools with less use of power and space. (Wang, 2002).

2.5.1 Electrical Discharge Machining (EDM)

Since electrical discharge machining is one of the most common machining processes, it is important to apply this process to micro-manufacturing systems, considering its advantages and outcomes. Furthermore, EDM machines can be miniaturised and fitted to Microsystems due to their simple mechanical setup and design (Beltrami*,* 2004), which can provide high efficiency and space saving opportunities.

Moreover, micro-EDMs have some advantages over other machining processes, such as cutting and drilling, because they are a non-contact machining technique using thermal energy like plasma, giving it the capability to produce high precision products with much fewer tool breakage problems. Considering the above advantages of EDM, it has been important to introduce Micro-EDM, keeping in mind the characteristics, advantages and disadvantage of this process.

In order to introduce EDM as a part of any manufacturing system, the basic principle of EDM must be identified first. This concept works through removing material by applying current discharges between the electrode tool and the work piece. Moreover, developments and changes have to be implemented in order to apply this method to a module, as recent studies in Korea have suggested adding a test bed to the module and platform as shown in (fig. 2.16).

This test bed consists of a surface motor, precision feed drive, DC power supply and control unit. The reason for applying these adjustments is to increase the efficiency for batch production using less space and fewer resources. However, applying these developments could result in some errors and malfunctions, which raises the need for more process control. In order to achieve this, a control method that is based on controlling pulse rate using real-time pulse counting has been introduced (Hayakawa, 2004).

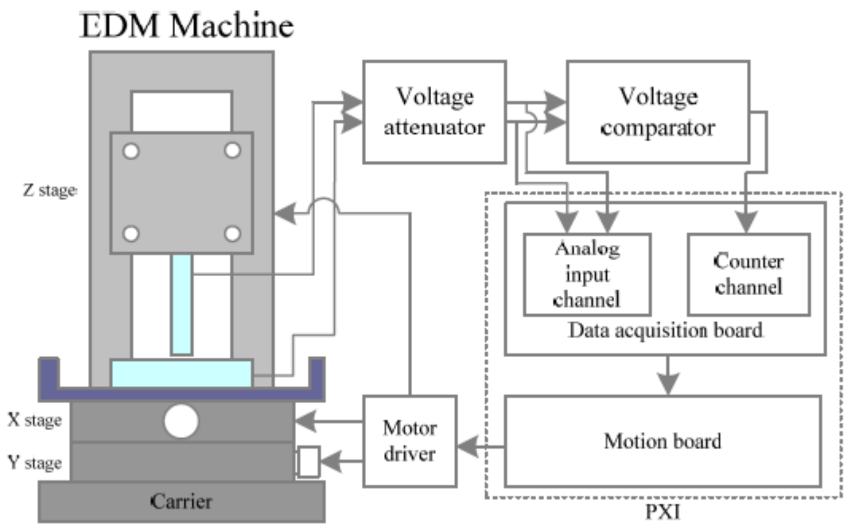


Figure 2.16: Set up of EDM machine (Hayakawa, 2004)

This method has efficiently increased the accuracy of the machining process using Micro-EDM module. Basically, this method is based upon using the relationship between the pulse rate and the gap between the electrode and work piece; it has been observed that decreasing the gap between the electrode and work piece will result in increasing the pulse rate, which will eventually control the material removal rate (MRR). Therefore, according to the increasing of this process precision and efficiency, it can be applied in several applications in manufacturing as follows.

2.5.2 Micro-Assembly Process

Micro-assembly is one of the most important applications in this field. Micro-assembly can be defined as "the assembly of objects with micro-scale features under micro-scale tolerance" (Yang et al, 2004). The assembly process in micro-system environments represents the association of mechanical and electronic systems, and the importance of this association is growing, due to the increase of the global market and demands for automated micro-assembly that are involved in producing a wide range of products such as hearing aids, hard disk drives, and sensors, etc. The main concept here is transporting small-components and being able to manipulate these components in order to fulfil certain tasks. There are essential tools and equipment that are required in performing any micro-assembly related task. These tools include a microscopic vision system equipped with a monitor that can record and provide feedback during and after the assembly process, which can also be considered as the first step towards modifying or improving this process.

Other tools include micro-position and micro-gripper tools, a micro-components handling and transferring tool with high precision and resolution and real-time computer vision which will be used in controlling and aligning the parts in assembly process as shown in fig 2.17.

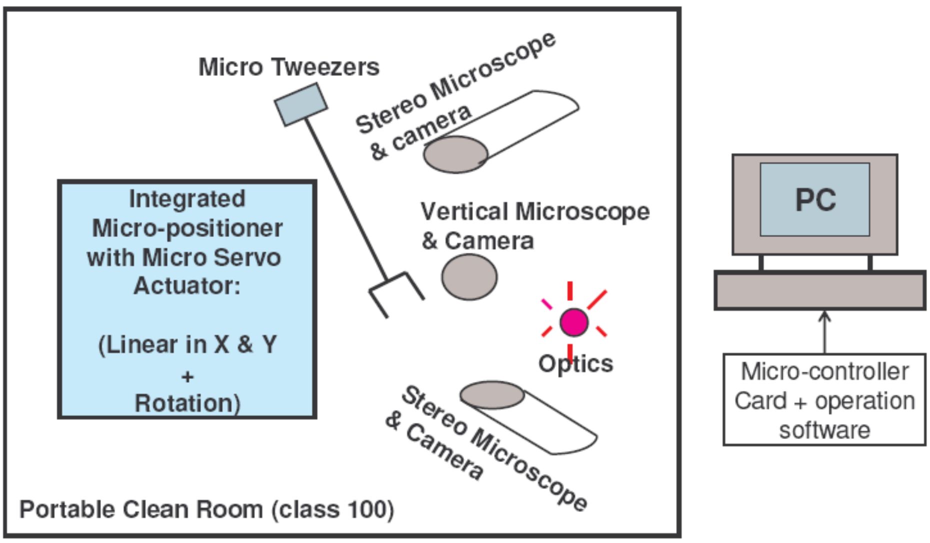


Figure 2.17: Requirements of Micro-Assembly cell (Pham, 2004)

In addition, micro-assembly is a complex process that consists of several applications such as manipulation and gripping. Each one of these applications will be described in detail in the following section.

2.5.3 Laser Applications in Micro-manufacturing

Laser technology has always been capable of providing top-class machining on a small scale due to the wide range of its applications like drilling, milling, cutting and surface finishing. This technology can also be used with several types of materials such as metals, ceramics, polymers and silicon (Oxford Laser, 2007).

Using laser transmission as a module in a reconfigurable micro-manufacturing system can provide several advantages such as increasing the number of applications that can be done by the micro-manufacturing system. Also, it can provide a unique process precision due to the ability of adjusting the laser beam through transmission.

The following three types of laser are used in micro machining: nano-second, pio-second and femto-second lasers. Each one of these types has independent applications and characteristics. For example, pio-second laser is suitable for working on areas of size between 4 and 50 micron and can be used for drilling and finishing processes within a specific range that mostly depends on the machined component.

2.5.3.1 Laser Micro-Milling

As mentioned before, lasers can be used in a wide range of micromachining processes and materials, and using this technology in a micro-milling process can mostly be done within certain conditions, such as choosing the laser type that suits the process; in other words a matching process between laser type and material should be implemented before starting any process (Pham, 2004).

Moreover, since lasers can work with different types of materials such as metal, ceramic and dielectrics, high quality products can be manufactured based on the produced features such as surface finish. Applying laser micro-milling on metal has always been considered a complex operation in industry since using micro-second laser results in poor product quality. This is due to laser melting and recast on the work piece. Therefore, a shorter laser pulse is being used in order to produce better results; so it is clear that surface roughness improves when the laser pulse rate decreases (Fleischer, 2005). Applying the same technique on ceramics requires process modification because of the different properties between metals and ceramics. A combination of short pulse and short wave length can achieve better results in ceramic laser machining.

On the other hand, Duley (1997) stated that applying the same technique on dielectrics can be limited by the fact the dielectrics are transparent to the most common laser beam lengths. So, he suggested using pio-second laser to avoid this problem and low surface roughness.

2.5.3.2 Laser Welding

Welding is another application of lasers in micro machining. This process has several advantages such as the laser transmission, which used in micro-manufacturing systems has low mechanical and thermal load (Herman et al, 1999). Also, a well-focused laser beam will result in producing high precision products with better qualities and features. Since this process is being used widely in plastic welding, these two technologies can satisfy the requirements of this process: mask technology and contour welding. Mask technology is based on placing a mask between laser sources and adjoining parts, in order to redirect the laser beam to an adjoining spot during the welding process (Zybko, 2002), this process can also achieve straight and curved welding.

On the other hand, in contour welding the weld is irradiated by the laser beam and melted on the same welding position (Haberstroh, 2003). The main advantage of this process is the flexibility and capability of welding three-dimensional shapes (fig. 2.18).

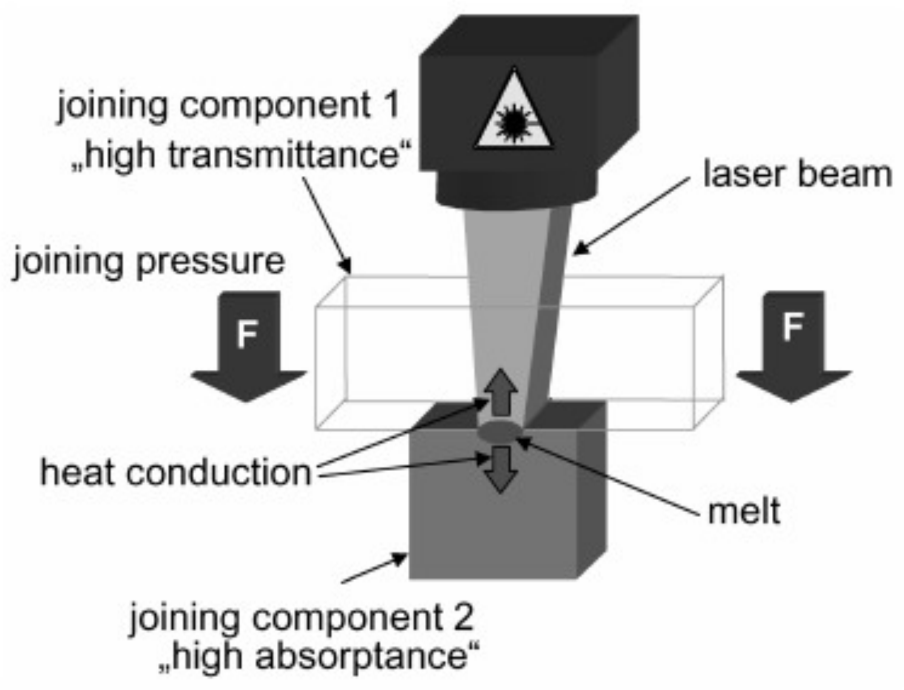


Figure 2.18: Laser Transmission Welding (Haberstroh, 2003)

2.5.4 Micro-Cutting Machining Processes

In most machining processes based on material removing techniques such as micro milling, drilling, lathe and engraving, the characteristics of cutting force, fracture of tools and wear of micro tools are greatly incomparable to the traditional tools (fig 2.19). So, direct as well as indirect wear control methods have been set up in order to enhance machining operations productivity. Tool tip optical scan is used as a direct method in order to measure the tool wear (Wu et al, 2003).

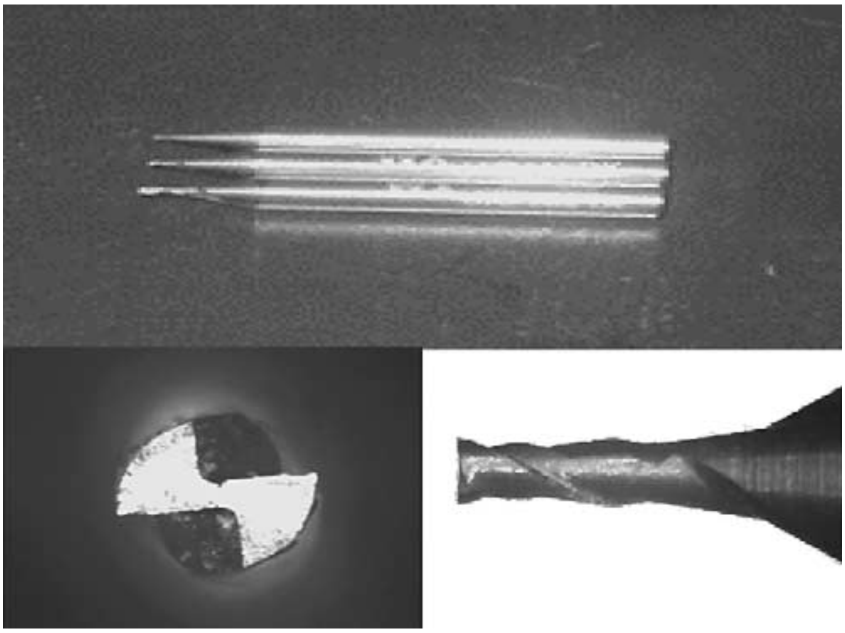


Figure 2.19: Micro end-mill cutter (Wu et al, 2003).

Cutting mechanics standards of minimum chip measurement effect and surface are the drivers of unique machining parameters within micro scale such as; acceleration feed rate and spindle performance. Micro-machined characteristics and the equipments employed to manufacture these characteristics (drills, routers, etc,) are within the range of 1mm to 10mm.

The spindle speeds of 38,000 rpm were selected by the dimensions of this equipment in order to gain normal surface speeds for stainless steel (150-300 m/min) and brass (60-120 m/min) (Chae et al, 2006) (fig. 2.20). Spindle technology is expected to show further improvements, as the currently available spindle technology can exceed the speed of 200,000 rpm (Schaller, 1999).

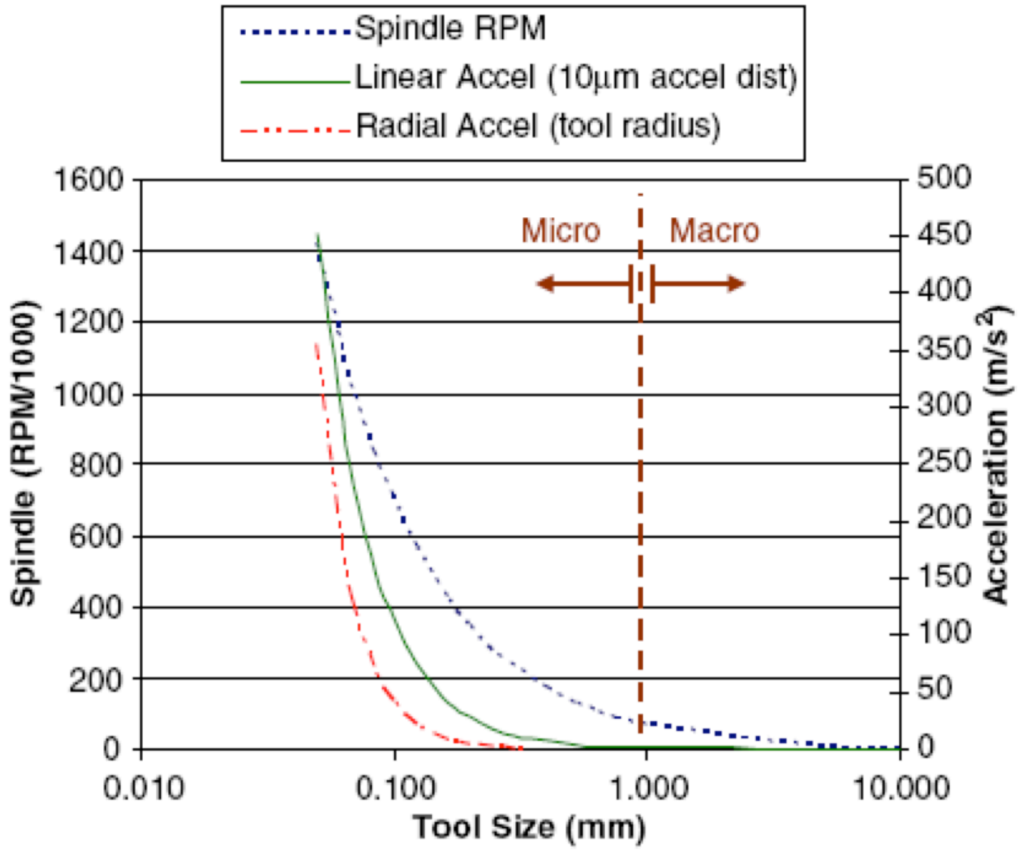


Figure 2.20: Spindle speed and acceleration requirements for various tool diameters (Chae et al, 2006).

One of the key aspects to affect any component's quality is surface roughness, which has been heavily involved in studies. Users of the traditional macro machine tools, including researchers, have developed dedicated theories as well as models. Micro machining started appearing on the surface and being noticed as of late due to the strides made within miniaturised industries. In comparison with macro-machining, micro-machining quality proved to offer further complications to maintain control. One of the significant aspects of the micro-machining analysis is the development of micro-components quality. A contribution has been submitted by several researchers to surface roughness within end milling (Yang, 2001).

2.5.5 Micro-Clamps and Positioning Tools

The first step in micro-manufacturing instruments is miniaturising the corresponding subsystems. In particular, micro-machine tools for material-removal processes have, as a key subsystem, a micro-spindle unit that must achieve high rotational speeds while maintaining good rotational accuracy for micro-feature machining (Shin et al, 2006). In developing micro-spindle units, a critical problem is miniaturisation of the tool-clamping part that holds the tool in the spindle. Approaches for scaling down conventional tool clamps, such as the collet-chuck, hydraulic chuck, and shrink-fit methods, may be limited by their inherently complicated structural and operational mechanisms (fig. 2.21). In collet-chucks, a tapered collet and collet-pulling device such as a spring and a screw must be included in the micro-spindle.

Figure 2.21: Clamping tool (Tansel, 2000).

Hydraulic chucks have a non-axisymmetric structure inside the spindle due to the need for an adjusting screw and oil paths. These elements unbalance the rotor mass, increasing rotation error motion at high-speed revolution (Weck et al, 1997). Finally, shrink-fit tool holders require specific equipment to heat the device to a high temperature to unclamp a tool; equipment that is too expensive and too large for use with micro-machine tools (Tansel, 2000 and Lim, 2003).

2.5.6 Measurement and Inspection Technologies

Measurements and inspection technologies have proved to be of immense significance in order to sustain a successful development of miniaturised machine tool within micro machining (Masuzawa et al, 1993). Therefore, it is important to maintain constant monitoring when performing micro machining tool-based processes, as this approach provides important feedback information regarding positioning, feed rate and accuracy of both machine tool and machined components as shown in fig. 2.22.

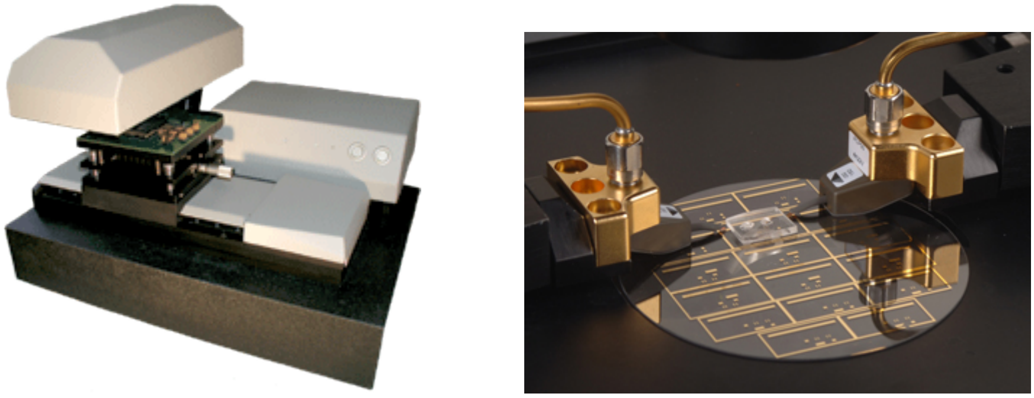


Figure 2.22: Ultra-precision micro-machining and positioning tools (Dornfeld et al, 2006)

For example, tool-based machining fabricated component accuracy can be achieved in case of maintaining the tool dimension during the machining process. Also, better control over tool changing schedules as well as process control can be sustained through in-process estimation tool wear within the machining process. Moreover, one of the key aspects of any high precision machining process is to provide a real-time monitoring process in order to maintain the required machining and production quality (Wilcox, 1997).

2.6 Recent Advances in Micro Machining Centres Designs and Solutions

Over the past few years, several machine tool manufacturers have introduced micro machining centres with various form factors to the market. Most of these machine tools have been developed aimed at providing a range of machining capabilities within scaled down machines. Also, these machine's centres are focusing on delivering a high level of production and utilisation by employing several manufacturing strategies such as flexibility and reconfigurability. In this section, an overview on some of the most recent micro machining centres is provided, highlighting key features and limitations that must be considered and analysed during the development of the novel reconfigurable micro machining cell (RMC).

The 3D High Precision Micromachining Centre by SARIX (fig 2.23) offers a combination of high precision machining processes based on EDM technology. This technology performs a range of micro machining processes including; drilling, milling, sinking and grinding in addition to other non-EDM processes such as 3D scope measuring and laser ablation.

Figure 2.23: SARIX MACHAero 8 axis machining centre (SARIX S.A, 2010)

The configuration of this machine centre can achieve a high level of micro machining accuracy +/- 2 microns, while maintaining a positioning accuracy of 0.1 micron. However, even with a small work envelop (100 mm^3), the relatively large size (W= 2200, L=2500, and H=2300 mm) and weight (2500 kg) of this machine centre categorise it as a high precision, conventional machine tool, as it fails to deliver certain characteristics of miniaturised machine tools including having a small footprint in order to reduce the required space and energy to operate.

The following design of desktop Factory (DTF) by Bosch (fig 2.24) is based on standardised basic frames and processing modules and plug-in units in a compact format representing a flexible material transfer system, where each plug-in unit is dedicated to perform one operation. Based on the processing process, several plug-in units can be flexibly lined-up in the frames.

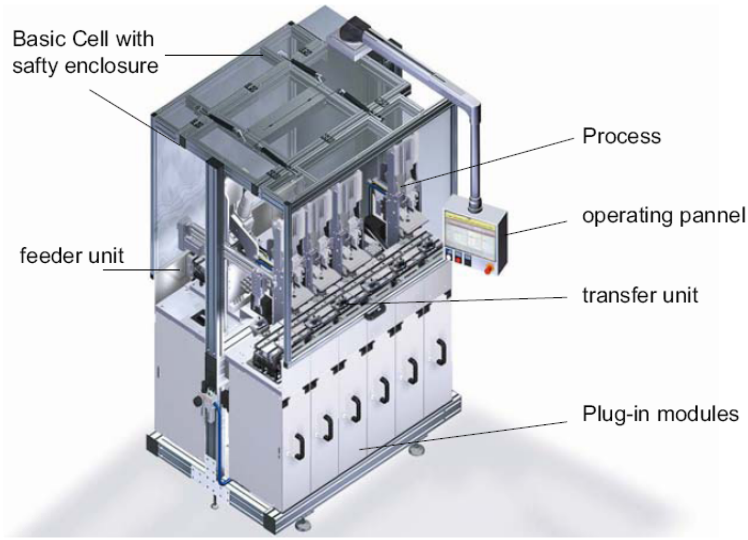


Figure 2.24 Standard Modules for Desktop Factory (Bosch Rexroth, 2006).

This design demonstrates several advantages of employing a standardised and uniform manufacturing cell. These advantages include allowing easier system upgrades and expansion in the future while maintaining low capital investment. It also increases the system's modularity and flexibility since each module can be designed to contain certain manufacturing processes. However, besides the standardisation of module design, this DTF can be categorised as a conventional production line due to its size. In addition, each module can only perform a single process, which means it will require several modules to perform more than one process on each machine component.

Another form of micro machining centres that can perform inspection and assembly processes has been introduced by Aerotech. These machine centres aim to provide a range of processes and applications on location. Figure 2.25 shows two designs for high accuracy inspection stations by Aerotech, whose designs were based on delivering stations with small footprint (1 m^3) and high performance. The key feature of these gantry-structure stations is their ability to perform both inspection and assembly processes on high-volumes of micro/macro size components. However, there are limits to how far these designs can be taken. These limits include the lack of performing several machining processes simultaneously, as there is only one processing zone in any of the stations, which only allows one module to process a single component. Such a design is suitable for high accuracy processing and repeatability. However, when designing a novel RMC, including more processing zones, modules and a wider range of machining processes must be considered to increase the productivity of the novel design.

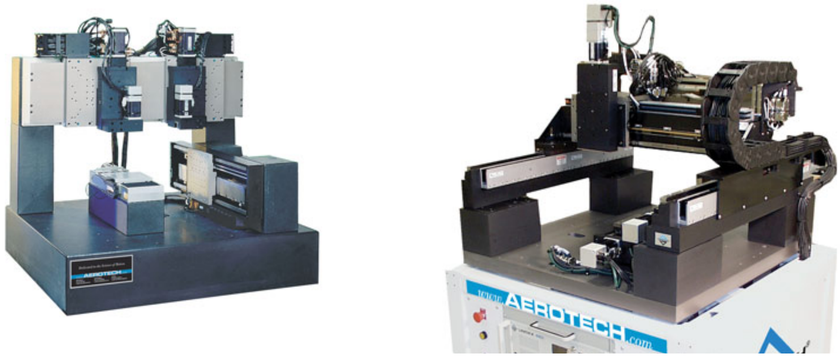


Figure 2.25: High accuracy inspection and assembly stations (Aerotech, 2010)

Figure 2.26 shows another example of an ultra high precision machine tool (UltraMill™) that has been built to deliver a trade-off between conventional ultra precision machines and micro factory machines (Huo et al, 2010). The UltraMill is a general-purpose ultra precision machine tool; it offers the ability to manufacture 3D miniature mechanical components and micro-featured surfaces in a wide range of engineering materials in a small footprint.

Figure 2.26: 5-Axis Ultraprecision Micro Milling Machine (Huo et al, 2010).

Moreover, three linear axes and two rotary axes have been included in order to achieve a 5-axis configuration. This configuration increases the flexibility of the machine tool and work piece orientation, which may result in increasing the required set up time between various machining processes. The significance of introducing this machine can be shown in the massive reduction of the overall size and footprint (1 m^2) compared to conventional machine tools. A machining envelope of 150 x 150 x 80 mm^3 is considered sufficient to work large size components.

Reviewing recent advances in machine tool design is a key step toward highlighting the specifications and capabilities of the reconfigurable micro machining cell in this research. This includes identifying key aspects such as overall size and footprint, machining accuracy and machining processes. One key feature that can be implemented in the design of RMC is the radical reduction in the machine's footprint (0.5 m^2) while maintaining a relatively large micro machining envelope of (100 mm^3). Another key feature is achieving a machine design that can be reconfigured to perform as a stand-alone system and as a part of a cellular configuration of several machines (production line).

2.7 Summary

This chapter has reviewed the state of the art of micro manufacturing systems with a focus on Reconfigurable Micro-manufacturing Systems (RMS). This review has included an analysis of RMS characteristics and market growth as well as some of its key features. A number of manufacturing strategies have been studied including cellular manufacturing (CM), point of use manufacturing (POU), design scalability and manufacturing process plan (MPP). The consideration of these strategies, along with a number of key advances in machine tool design and technology, has helped highlight the boundaries and potentials of this research. Also, it has confirmed that a novel design for a reconfigurable micromachining cell can be developed based on combining these strategies and solutions.

A framework to develop the novel design will be discussed further in the following chapter, stating each stage of the development process.

Chapter 3:

Development Methodology

Chapter 3 - Development Methodology

3.1 Introduction

The design approach which was followed in developing the Reconfigurable Micro-manufacturing Cell (RMC) focuses on progression of the state of the art as well as satisfying the aims and objectives of this research. This type of design methodology is considered more suitable for this research project since it is based on reviewing and evaluating past work and available technologies in order to come up with a new product development process. It also allows performance of a continuous optimisation process with the aim of achieving a final product of better quality. In this research, the key design feature of the proposed architecture is the concurrent processing component that uses multiple machining centres on the same frame. Performing several machining processes concurrently is quite a challenge, and several considerations concerning the operation of the machine, as well as the design of the machine itself, have to be taken into account.

3.2 Framework

After reviewing several ranges of RMS applications and design characteristics, as well as several manufacturing strategies in the previous chapter, it is now possible to develop a list of requirements and specifications in order to start designing and building a novel RMC. Moreover, the process of reviewing previous work in RMS can be justified by the need to develop a full understanding of the research areas as well determining and evaluating the research originality to achieve a possible increase in the added value of the research field. Benefitting from previous experiences and projects can be achieved by avoiding common setbacks and saving time. Also, this step will result in defining the research area by setting the required resources and potential outcomes.

Furthermore, specifications of the concept will be addressed before conceptual designs start to be developed, as setting operation targets and machining capabilities such as machining processes, system's geometry and footprint, material used, level of reconfigurability and project budget is considered as a set up requirement before initiating this design process. Following this, a more detailed specification sheet can be developed based on these requirements and available resources.

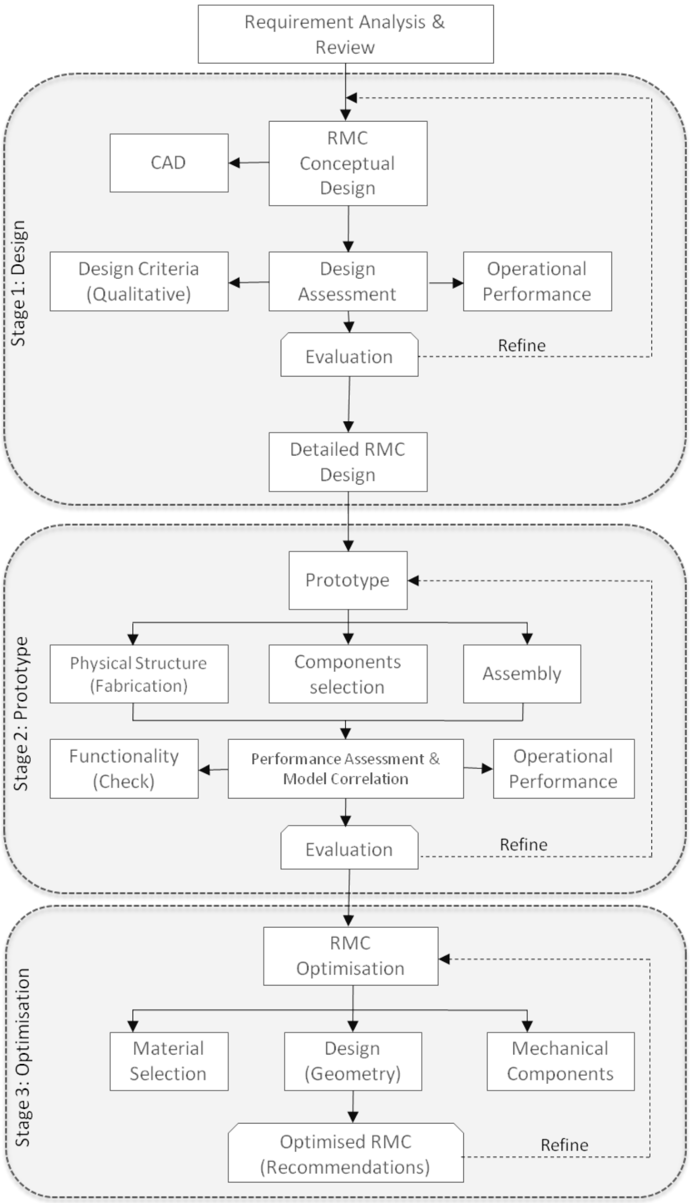


Figure 3.1: Framework to develop a novel RMC.

In order to develop a novel RMC, several steps need to be fulfilled in order to achieve this. In this research, a work approach (fig. 3.1) consisting of several stages is used in order to come up with a proper novel design for a micro manufacturing cell. This includes evaluating, designing, testing and prototyping a novel concept based on certain specifications and requirements that will be mentioned in detail in this section. Given the various components and modules in the proposed framework, it is noticed that several design and implementation challenges need to be addressed in order to come up with an appropriate conceptual design and physical model. This iterative approach also allows consideration of more alternatives and assists in the management of the design

process, i.e. capabilities, control, evaluation and configuration of the components and manufacturing processes.
The proposed framework of the RMC conceptual model and prototype can be continuously improved with the design object continually refined. The proposed design analysis and prototype testing can perform a very important role in developing and improving the overall performance of the system during each stage of the project.

3.2.1 Stage 1: Conceptual Design

The first stage aims at generating detailed three-dimensional model based on pre-identified design specifications. This part involves using a CAD system to develop a conceptual design, which is applicable since the following two kinds of design are practiced: evolutionary and revolutionary design. Evolutionary design is considered a common technique in developing products, and focuses on producing a new design based on a previously defined list of physical and operational specifications and requirements,. This approach is considered highly suitable for this research as it follows a logical set of design-developing procedure as will be described later. Moreover, evolutionary design impacts several design and production factors including financial, reliability and safety aspects (Bozzo et al, 1999 and Bourinet et al, 1999).

Furthermore, building a library of CAD files based on process designs will help achieving a more utilised developing process as it reduces the required time to design and build a new products according to Harrington (1998).

Then, finite element method FEM is used to analyse the conceptual design and compare its performance a previously set list of requirements. The main reason for using such a method is to solve mathematical formulations that considered too complex to be solved analytically (Bathe, 1997). This analysis process represents the first step towards the assessment process in this project.

Once a concept is designed and assembled as a 3D model and material is selected, it is important to perform a design assessment process. This process involves performing two different sets of assessments. The first set focuses on testing the operational performance of the design by predicting its performance under several operating and machining conditions. This also provides an overview of the design that is mainly related to characteristics such as stiffness, natural frequency and weight, all of which have an effect on how well the concept will perform the task it is designed for. The second set of design assessment is focused on the qualitative aspects of the concept. This means it works as a checklist to ensure that the design satisfies and fulfils the manufacturing strategies and machining processes such as re-configurability, POU, and CM strategies.

Next, the performance of the conceptual design is measured based on the entire set of criteria relevant for the evaluation, and at the end a list of refinement points will be developed in order to amend the design using CAD and performing the same assessment process. Finally, once a satisfying design is reached, detailed design drawings and specifications are generated in order to start development of a physical model.

3.2.2 Stage 2: Prototype

Once the previous stage of generating a 3D CAD model of the proposed design, the process of building a prototype to demonstrate the selected design can be started. This process consists of three main tasks, including fabricating the physical structure, selecting sub-system components and assembling all these parts as a system. Building the machine's structure involves dealing with a material selection process to build the main part of the system. This includes fabricating components such as the machine's base and supports, while a component selection task involves acquiring mechanical components and software such as machine tools, fastening components and a control system. Moreover, when designing a machine tool for certain performance and accuracy, one of the most important criteria is the effective stiffness between the tool and work piece interface. Therefore, it is important to consider the effect of each part within the system in order to come up with a correct indication of the entire system performance.

Following that, there is the assembly of individual parts, each of which has a finite stiffness. However, some of those components can be more significant to the structure of the system, which can be noted during the assembly process where the rest of the components are affected by the performance of parts that are involved in the structure of the system. The stiffness of these components has a major impact on the accuracy of a machine tool. Hence, it is essential to consider the effects of such elements as early as possible to accurately predict the performance of machine concepts.

Once all of these components are assembled, a second performance assessment process will be conducted, aimed at measuring the overall performance of the physical model and developing a valid correlation between its performance and the FEA model from stage 1. This includes testing the prototype when several forces and machining conditions are applied and checking the functionality of the model and its ability to perform and deliver the required manufacturing strategies and required design criteria. Based on the results of this assessment, a refinement process needs to consider how to improve the performance of the physical model or modify the conceptual design.

3.2.3 Stage 3: Optimisation

The outcomes of the previous two stages will be used as a starting point in the optimisation process, which is required to increase the quality and productivity of the model. The optimisation process in this research includes applying three levels of design modification, such as experimenting with different types of material for machine structure, modifying machine structure geometry and acquiring new mechanical components in order to examine the performance of the RMC under all these modifications using its performance from stage two as a benchmark. Finally, a list of recommendations to optimise the design will be generated as a part of the refinement loop of the process, aimed at providing full knowledge of the design and suggesting an optimisation list to build better RMC prototypes in the future.

3.3 Summary

This chapter has described in detail the framework and design methodology which will be followed in order to develop a novel design for a reconfigurable micro-manufacturing cell. This methodology consists of three main stages (design, prototype, and optimisation), and each stage includes a feedback loop. The following chapter will provide a detailed illustration of the first stage which involves designing the novel RMC whilst including a design performance assessment process.

Chapter 4:

Designing a Novel RMC

Chapter 4 - Designing a Novel RMC

4.1 Introduction

Reconfigurable manufacturing systems (RMS), whose components are reconfigurable machines and reconfigurable controllers, as well as methodologies for their systematic design and rapid ramp-up, are the cornerstones of this new manufacturing paradigm (Moon, 2000). The idea of RMS goes beyond the concept of modularity as these systems allow mass customisation, facilitate easy integration of new technologies, are cost-effective and provide high-speed capability. Design methodology, design verification, and prototyping processes present a scientific basis for designing RMS based on pre-determined process requirements. The following issues need to be analysed and fulfilled in order to develop a novel RMS:

* Developing basic building blocks (modules) of the system.
* A method of representation of modules that sets up the system's requirements.
* A method of representation of performance assessment and analysis.
* Developing a design optimisation strategy.

This chapter will describe the process of designing a novel RMC, providing design iteration and assessments of several conceptual designs, followed by selecting the final design which will be employed throughout this research.

4.2 Design requirements Analysis

Before starting the development process of a novel RMC, a number of design and performance aspects must be listed and identified, aimed at delivering and maintaining a high quality end product. This developed product will be used in a later stage as a start point of an optimisation process, which involves building a physical model of the concept allowing further design and performance optimisation processes in the future. Following stage one from figure 3.1 (Framework to develop a Novel RMC), starting a conceptual design requires developing a set of requirements and criteria, which will be used to evaluate the design in a later stage.

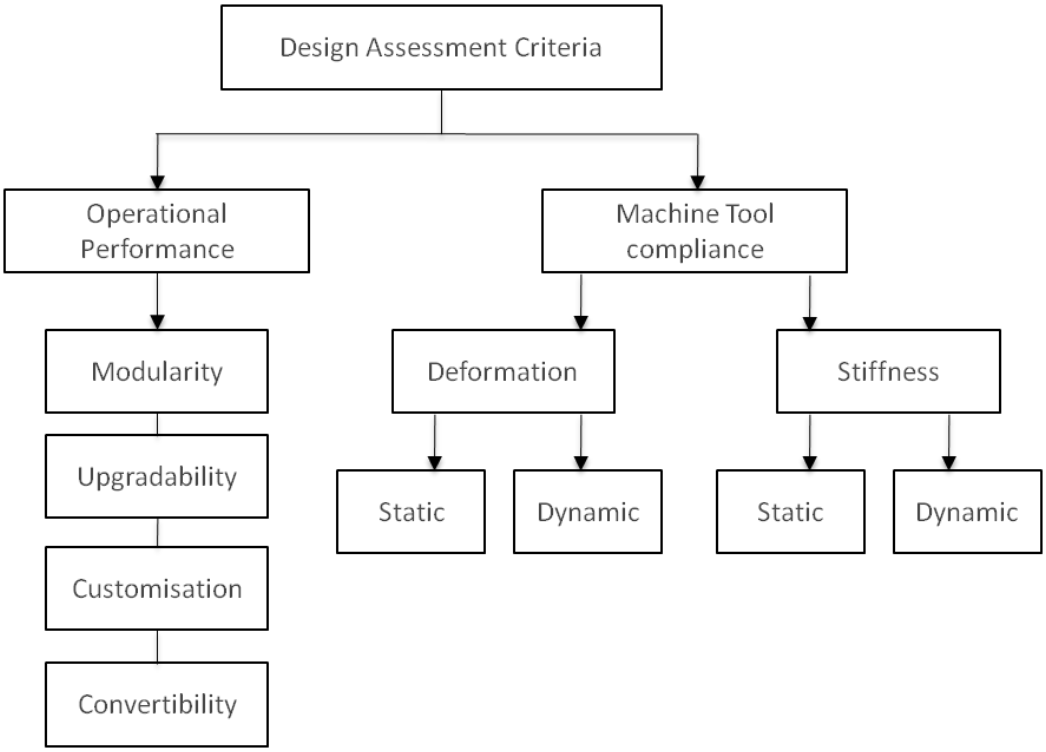


Figure 4.1: Design assessment criteria

As shown in the above figure (4.1), two sets of assessments will be used to evaluate the design of RMC. First, is operational performance based on qualitative aspects that focus on evaluating the adoption manufacturing strategies such as Cellular Manufacturing (CM), Point Of Use (POU), design scalability and Re-configurability. Measuring certain design capabilities including, modularity, upgradability, customisation and convertibility can do this. The second set of criteria is based on testing the structural performance in order to provide an understanding of the system's performance under various operating conditions. This assessment will measure both static and dynamic states of deformation and stiffness, allowing better comparison criteria between designs.

Starting with the system's customisation, this characteristic defines the following two aspects: customised flexibility and control. Customised flexibility indicates that the proposed concept is built in order to perform a range of machining processes using a defined set of machine tools and components. Examples of machine processes include high precision drilling and milling processes. This type of flexibility represents the ability of these components to perform the required processes in different locations and positions within the footprint of the system.

Furthermore, by developing a reconfigurable design, the utilisation level of the system can be improved by increasing the number of the processing modules. This step will provide the capability of performing more processes such as machine assembly and turning, which can be applied for a low-cost reconfiguration process in order to increase the overall flexibility level of the system. Alternatively, customised control can also be introduced in order to manage and control any required physical process within the system. However, such a high level of process and machining flexibility indicates that a more complex control system is needed in order to satisfy the required level of flexibility and re-configurability.

Implementing modularity within the system is a result of applying cellular manufacturing, reconfigurability and design scalability. The proposed system will be designed to be modular in certain areas such as, structure and mechanical components, including spindles and linear stages, in order to allow inter-changeability, and the control unit. In a later stage, implementing modularity will be considered as a key element in the mechanical components selection process, since each one of these components will be selected based on its ability to provide more than one machining process. The convertibility feature is considered in order to fulfil the requirements of producing a wide range of product families using the same machine tools and set ups. The conversion process between the system's components has to be completed smoothly by changing the orientation of tools, fixtures, control unit and degrees of freedom. This step can be done by setting up pre-defined requirements of the production processes based on the specifications of the machined parts and final products.

In this project, mechanical elements and control modules are designed with interfaces for easy component integration and replacement. These are aimed at implementing key design features, such as Plug-and-Play, which can be identified as an enabling technology for rapid integration on a subsystem level (Graven et al, 2008). The introduction of Plug-and-Play (PnP) technologies to facilitate rapid integration between the system's components can have an impact on any complex system which can be seen in improvements, performance, cost, and schedule. This feature can be used to demonstrate the collaboration of all design criteria within the proposed concept.

The integrated machine performance may be predicted according to the performance of its components and the interfaces of both software and machine hardware modules. Also, one of the anticipated design features of this concept is the ability to cope with any future market demand, which includes changes in production strategy and machining processes. Considering such a feature during the design process will provide the concept with a potentially higher utilisation level and production value due to the capability of maintaining the same production platform for a relatively longer period of time which will eventually reduce the need to re-design and produce new platforms in order to satisfy the new market demand.

4.3 Design approach and assessment criteria

During the early stage of this research, several conceptual designs for a reconfigurable micro-manufacturing cell have been considered. The aim of these is to develop a novel design that can satisfy and deliver the stated principles and requirements (Shpitalni, et al, 2003). This process follows an iterative design loop described earlier in (fig.3.1), which focuses on analysing each design aspect and functionality in depth before moving to the production of the prototype.

This stage of the research concentrates on the theoretical model of the concept, which means providing full analysis of the overall capability and performance using assessment tools such as design Finite Element Analysis (FEA) and simulation and design modelling. The main purpose of using these tools during this stage is to minimise the required time and cost to analyse the concept's performance and capabilities. Due to the complexity of the project, several design concepts have been developed demonstrating novel designs for a re-configurable micro-manufacturing cell. Therefore, a detailed design assessment process needed to be performed in order to test each concept. The result of these assessments will highlight the advantages and disadvantages of each concept, which will lead to choosing one of the designs to be prototyped.

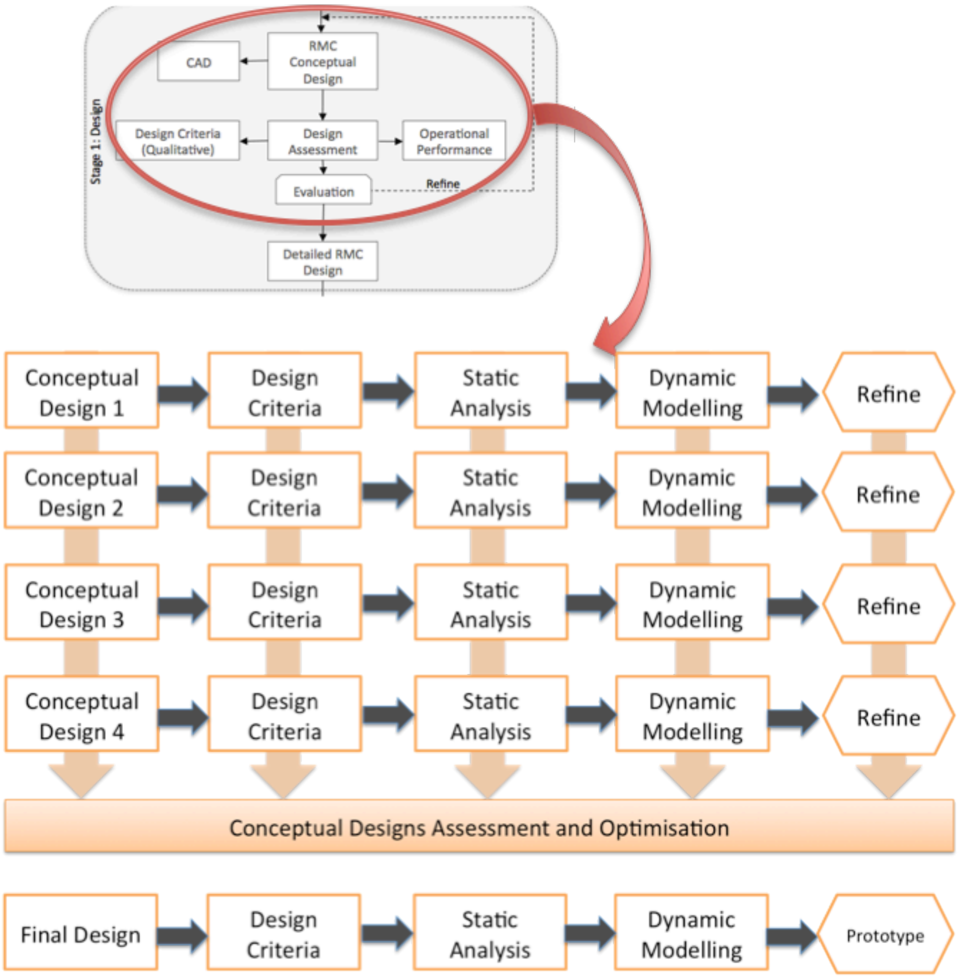


Figure 4.2: Conceptual design and assessment methodology.

The following part will present the initiation, analysis and assessment of four design iterations in the process of developing a novel RMC. Single assessment methodology is implemented in order to assess each design. This methodology consists of five main stages as shown in figure 4.2. Following the design methodology stated earlier in chapter 3, the design iteration in this research has four loops where each design is based on refining and modifying the one before. Finally, a fifth design is based on optimising the four previous designs and will be used to build the physical model (prototype).

By starting with developing a three-dimensional design, using Computer Aided Design (CAD) tools based on pre-determined design criteria, a material selection process will take place based on providing the required stiffness, suitability, availability and cost along with other processes including the selection of mechanical components and a control unit. Following this, the next two steps of the methodology involve performing an in-depth model analysis, which consists of providing a static analysis, based on studying the resonance (Natural Frequency) of the structure. The significance of this step can be presented in defining the behaviour of the system's components once an external force is applied. Analysing this behaviour will provide a better understanding of how these components will respond as a fully assembled structure. Based on this analysis, the overall performance of the system can be assessed in order to be improved and optimised at a later stage.

The next part of the modelling process involves developing a dynamic load assessment, based on the dynamic performance of each component in the system, while performing a machining process. The key aspect of this assessment is to examine the machining stability of the entire structure, by measuring the vibration level, which will be observed as physical displacements of the machine tool-heads. Ultimately, all these aspects will affect the level of overall accuracy of the system and the quality of machined parts.

4.3.1 Modelling Methodology

This part will provide an individual overview of each design, starting with several design aspects such as layout, mechanism and main components in addition to listing design advantages and limitations. Following this, each concept will be subjected to an in-depth comparison based on overall performance and productivity. This approach will rely on specific Computer Aided Design (CAD) and analysis such as ProEngineer, ANSYS and Mechanica to generate three-dimensional models and perform Finite Element Analysis (FEA) of the proposed design. FEA is known as a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as of integral equations. This analysis consists of a custom-designed computer model of geometry, design and material that can be modified to model and assess suggested conceptual designs in order to come up with a satisfying design of products. Implementing such a modelling analysis is common when developing new designs as well as applying refinements to some existing ones, aiming at providing a comprehensive analysis of these new designs during pre-manufacturing and production stages. In addition, when modifying existing designs, this approach helps providing several optimisation criteria based on a range of production priorities including cost reduction, time-to-market and sustainability.

Considering the increased complexity of delivering new designs to the market, two-dimensional analysis can be considered less suitable due to the lack of accuracy and details of the end design unlike three-dimensional analysis. However, selecting which type of analysis to use in any design process mainly depends on the complexity of the design itself, and when using any of these type an algorithm is required to define if a linear or non-linear deformation must be considered within each system.

In this research, the process of design analysis and assessment will be performed in several steps. Firstly, by drawing a 3D model of each part; this model includes details of the part's dimensions, tolerances and material properties. All individual parts will then be assembled by applying a number of constraints based on the way each part will be attached to the other. This approach offers more flexibility, to amend and modify the design of each part in the future, without the need to re-draw the entire 3D model if changes are applied. This is considered as a key feature in most CAD software as software such as these (including Pro Engineer) handle the assembled model as a tree of parts, where each part can be modified individually.

Generating a MESH of the proposed three-dimensional model comes next. A MESH can be defined as a grid of a complex system of points called nodes. The reason for performing such a process is to include material and structural properties of the design during the calculation process of the structure. These properties will define how the structure will react to certain loading conditions in both static and dynamic modes. Therefore, areas with more surface features, or under large amounts of stress, usually have a higher node density than those that experience little or no stress. The generated MESH will highlight any geometrical features in order to prepare the structure for further analysis. This will be described later.

Performing a static analysis using the previously generated MESH is done next by applying a load of 500N on the structure. This step will result in developing a range of natural frequencies (NF), which will be analysed in order to study the reaction of the structure in the static mode. The dynamic response of the structure will also be analysed by applying a certain load (50N) in order to measure the structure's reaction. Finally, the collected data from all four designs will be used to perform a performance analysis as part of the optimisation process to develop an optimised concept. The development of the new concept can benefit from this process by having more optimised design, geometry and material.

4.4 Design iterations

4.4.1 Design iteration 1: Re-configurable Machine Cell

The two main modules that contain all subsystems, components and tools as in fig. 4.3 represent the proposed cell. The first module is a processing unit that is responsible for performing the actual machining and assembly processes. Several interchangeable machining heads are attached to a central base, which provides a service to these heads. A combination of material handling, storage and transfer components represent the second group. These two modules operate cooperatively in a cell arrangement with a footprint of 1030 mm by 710 mm by 1122 mm (Fig. 4.4). This arrangement is designed to process components with a maximum volume of 100 mm^3.

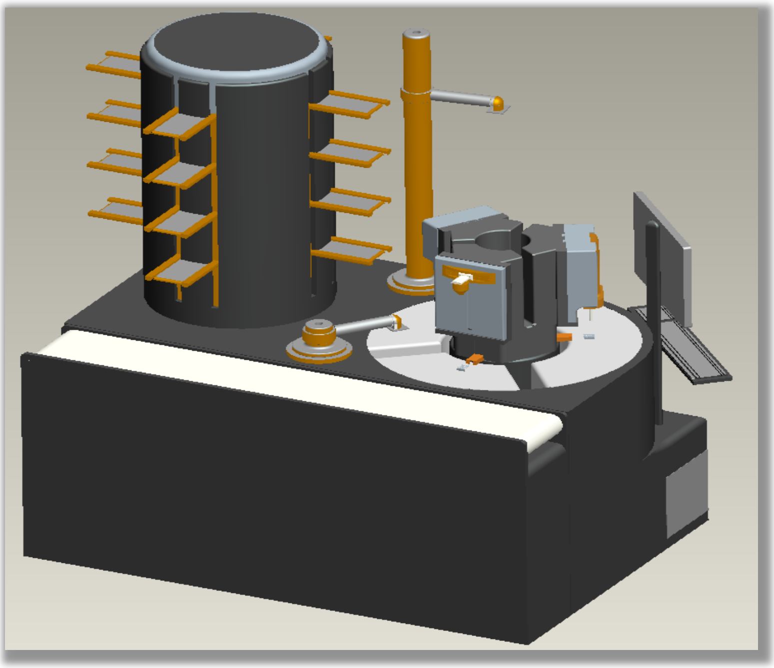


Figure 4.3: Overview of a Re-configurable machine cell.

In this design iteration, the focus will be on the design and performance of the processing module since it represents the micro-manufacturing cell in this design. However, other supporting systems and sub-systems have been designed at this stage, aimed at providing an idea of several systems collaborations and at integration as a system.

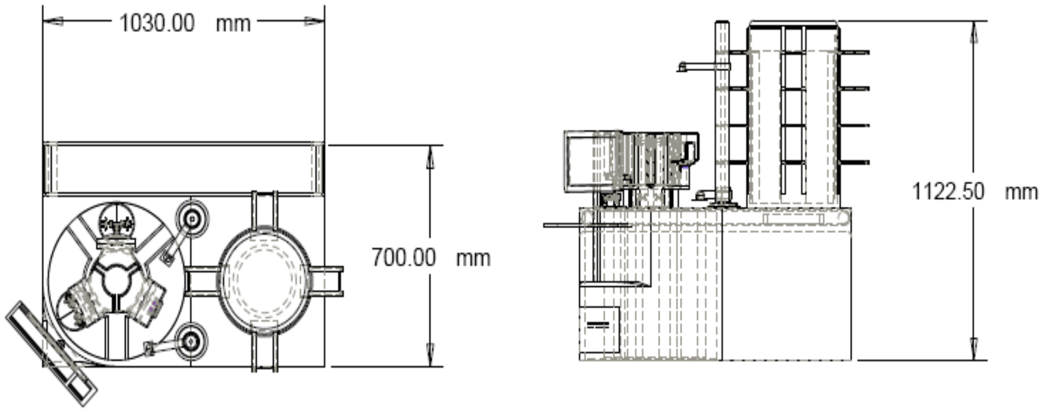


Figure 4.4: Footprint and dimensions of a Re-configurable machine cell.

The processing module, which consists of three main components that work in collaboration to manipulate, hold and machine each work piece in the system, is designed to perform a number of high-precision machining processes to produce high-quality products. Several design criteria have been considered. These include enabling tool heads to be replaced quickly in order to reduce the required set-up and production time.

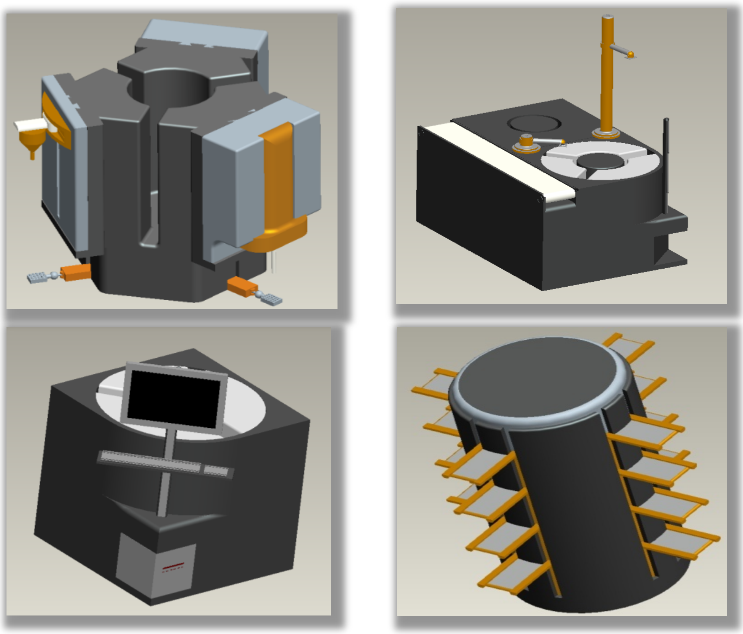


Figure 4.5-4.6: Overview of the re-configurable machine cell main modules.

This entire module is designed to be rigid and stable enough to cope with the required level of precision and performance. These issues represent major design challenges. An indication of such challenges is provided. The base is hexagonal with granite being the material of choice since granite is widely used in building high precision machines and also has a very small coefficient amount of thermal expansion, making it a suitable material for machine tool applications.

The hexagonal shape allows the fitting of up to three different processing heads into three of the base sides. The other module within the system is responsible for holding, transferring and storing the machined parts within the system. These processes can be completed using several units such as a robot arm, buffer unit, material holding fixtures and a conveyor belt. The main part of this module is the modular control system, which controls each unit in the system in order to achieve the desired efficiency and flexibility (fig. 4.5-4.6).

The main task of the buffer unit is to accommodate machined parts during each production stage, such as raw material (pre-machining), work-in-progress (during machining) and finished parts (post-machining). The mechanism of the robot arms is based on precise positioning and pick-and-place techniques. Meanwhile, the conveyor belt has the simple task of moving the finished parts from the cell in order to machine new raw materials. It consists of a solid base with dimensions of 1000mm long by 140mm wide.

4.4.1.1 Re-configurability and Productivity

This design allows any selected combination of machine processes to take place by setting up a suitable processing head. This means providing the ability to perform more machining processes on a single work piece at the same location. Hence, the production time and cost will be reduced since moving the machined part from one production line to another will be unnecessary. This strategy can be obtained by following a number of steps during the design and pre-production stage: The first step is to state the desired machining processes based on the design and specifications of the machined parts. Next is designing the tool heads to hold the required parts and components of each machining process, ensuring that the processing heads have the same structure and contact components as the module's base.

Attaching processing heads to the base can be done next by using techniques such as "plug & play". In addition, four mechanical contact points placed in the corners of each head must be tightened; using screws in order ensure correct positioning, and more contact and gripping between the processing heads and the base. This provides more flexibility and productivity to the production process within the cell. At this point, a dedicated control unit will take over on several automated processes such as the calibration of the tool head, compensating the wear of tooltips and performing the actual machining processes (Al-Sharif et al, 2008).

During the design of this cell the following two main levels of re-configurability have been considered: machining and operational re-configurability. Standardising several components in the cell to increase its flexibility can be considered as a possible solution in this project. To achieve this solution, each side of the hexagonal base is designed to provide a standardised interface for processing heads and also has common services such as cooling fluids, work piece holding and manipulation, control and power. This allows the installation of any processing head into any side of the base that is designed with the same interface. A flexible fixture allows the holding and manipulation of the work piece, providing additional degrees of freedom to a machining process including gripping, flipping and rotating (Lee, 1997). Due to the layout and configuration of the system's components, operations like monitoring, cleaning and maintenance can easily be performed in a short timeframe.

4.4.1.2 Design Analysis

Validating such novel architecture is a crucial step in the design process. Static and dynamic analyses have been performed to assess this design using finite element analysis (FEA). The results of this analysis are presented in this section. Considering the material of each the components mentioned, performance levels and an assumed natural damping level of 2% for each module, six natural frequencies have been observed. These are 475.8 Hz, 510.2 Hz, 692.3 Hz, 812.9 Hz, 873.2 Hz, and 1208.6 Hz. For each of these, the maximum dynamic displacement and stress have been calculated (Figure 4.8).

Figure 4.7 shows that even when contact areas between the base and processing heads are under stress, the base is considered to be in a stable condition. The second step was to calculate the maximum dynamic displacement during each mode. This is a key step in estimating the stability and precision of each machining process. Therefore, the damping level can be increased in order to have more precise processes. The results show better stability since the displacement of the processing module was reduced by almost 50%. This means providing more precision to the machining processes (Al-Sharif et al, 2009).

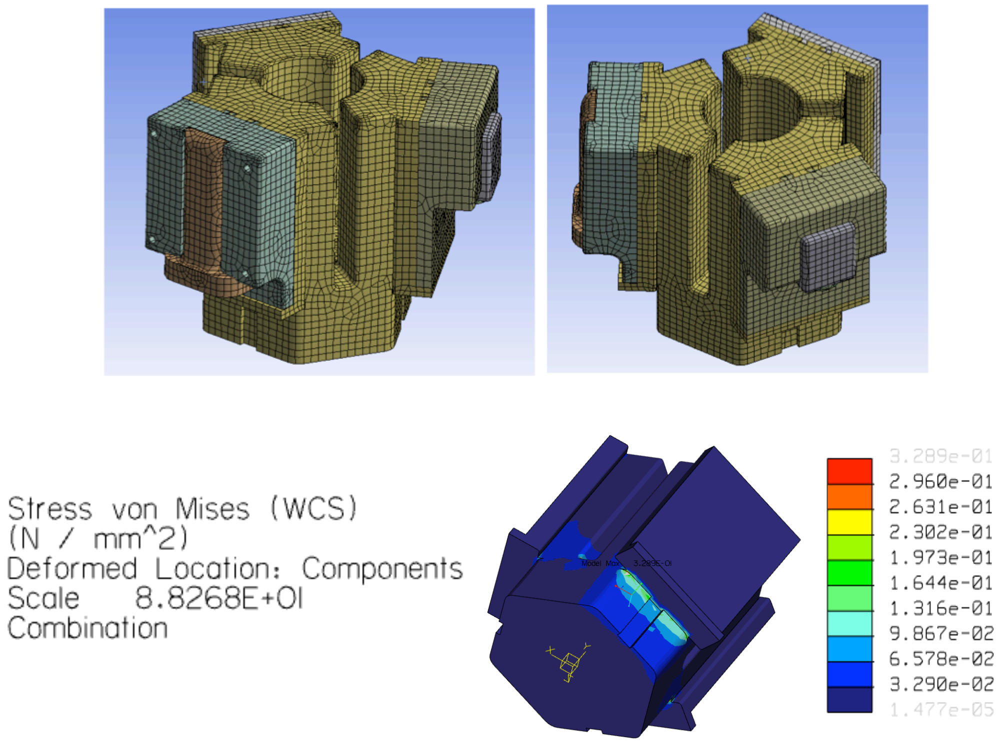


Figure 4.7: Mesh and static analysis when loads applied on the granite base.

Here, a static analysis has been done to study the reaction of the granite base with all three processing heads attached to it. Since a processing module will perform all machining processes where tool-heads are located, the performance assessment process will focus on this part of the cell.

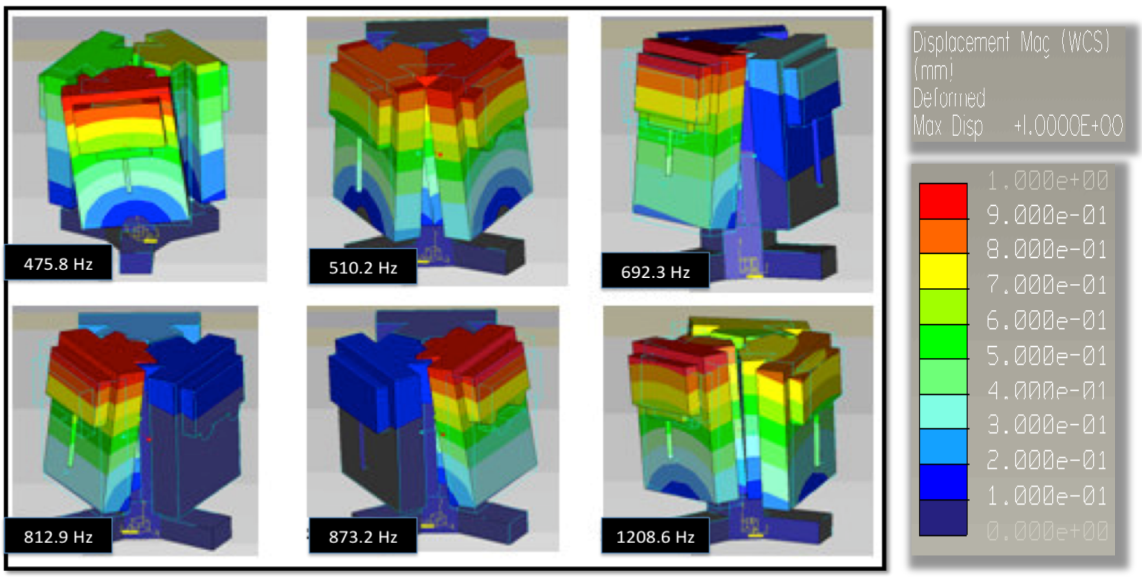


Figure 4.8: The system's Natural Frequencies in six modes.

4.4.1.3 Design Limitations

In this concept, several processing modules are represented including machining and buffer and control modules, where each module is designed and dedicated to perform certain tasks. This approach is functional as a RMC where there is a combination of modules and points demonstrating a sequence of stages to produce a final product from raw material. However, designing a control system to manage each step of the production process has proved to be a very complex and costly task. This will affect the capability of upgrading and optimising the system in the future, especially when other material, products families and quantities are considered due to market demand.

In addition to this, having several sub-systems working as individual units within the proposed concept will have an impact on the overall machining accuracy of the processing module due to vibration resulting from operating each module. Furthermore, due to the size of the system, including dimensions and footprint, which reduces the mobility and portability of the structure, implementing key manufacturing concepts, such point-of-use and point-of-care, is highly unlikely to succeed.

4.4.2 Design iteration 2: A Re-configurable Desktop Machine Cell

In an attempt to develop a second conceptual design for a re-configurable desktop machine, the following ideas had to be considered in order to distinguish the second design following an intensive process of concept and design optimisation in order to cope with new design and production requirments aiming at adding more competitive charactarstics to the re-configurable desktop machine cell. Highlighting such an aspect was a result of state of the art review and market research.

- Design a relatively smaller footprint to obtain concepts such as Point-of-Use (P.O.U) manufacturing and Portability.
- Increase the number of processing modules by reducing other supporting sub-systems.
- Minimise the material handling process within the system.
- Off-the-shelf components must be considered before the design stage. This is important as the specifications of the mechanical components will affect the design of the concept directly by determining several design features such as layout, material and damping conditions.

4.4.2.1 Layout and Footprint

Two different processing modules have been considered within the system, which has a footprint of 500 X 500 mm (fig. 4.9). However, both modules have similar components and working mechanisms.

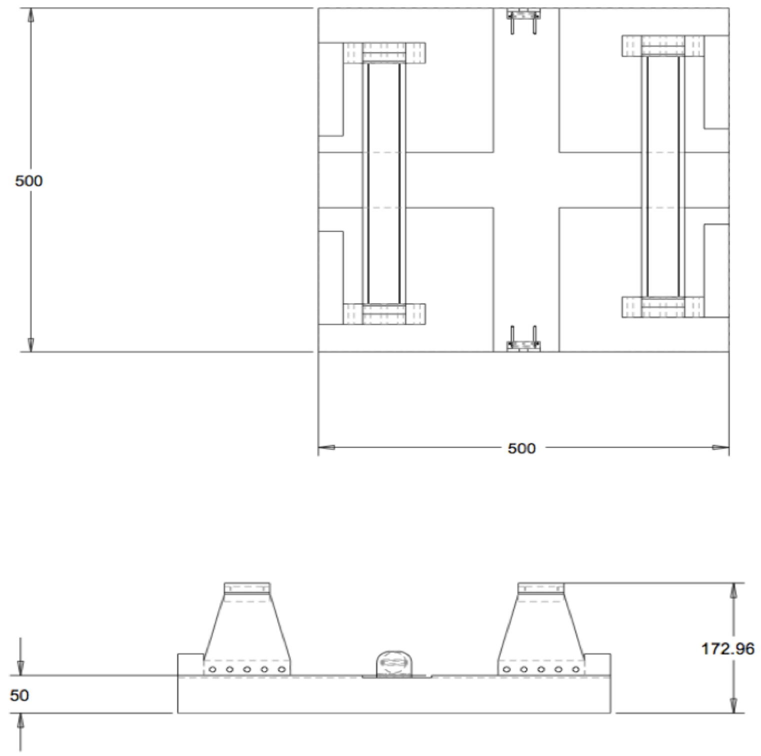
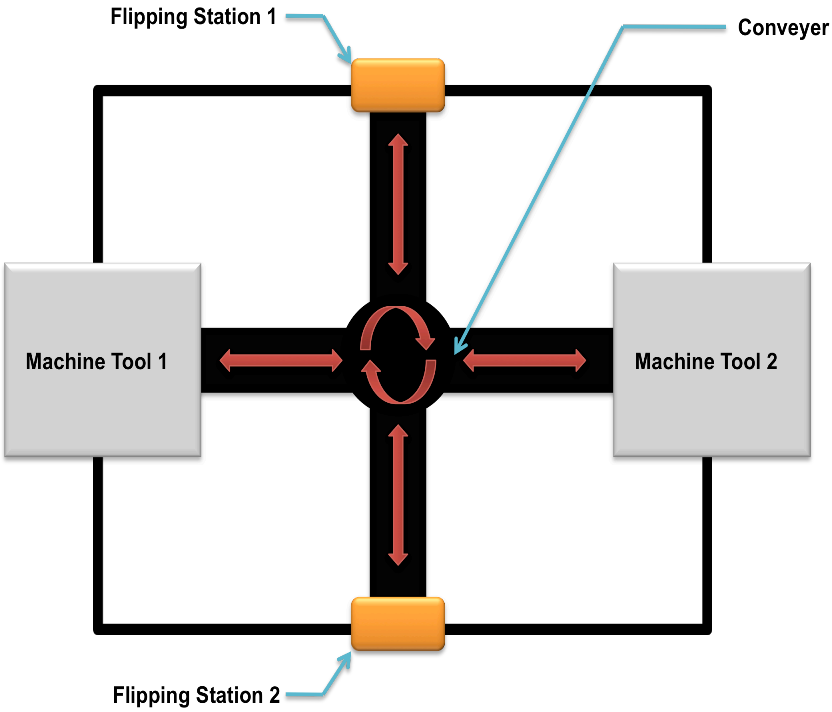


Figure 4.9. Design size and footprint (in mm).

In this layout (fig. 4.10), each module is placed on the ends of a conveyor belt. Each unit demonstrates a certain level of flexibility by performing several machining processes. Also, in order to be able to machine both sides of the work piece, two flipping units are included.

The modules consist of double-gantry structures with a lathe machine attached to one of its sides. This structure can be reconfigured to perform up-to three different machining processes. For example, a drilling, milling and turning process can be fitted to the gantry structure. Fixing the work piece in three different locations can perform these processes. Also, point-of-use concept has been considered here and can be shown in several design aspects including size reduction and change in layout, which emphasize portability.



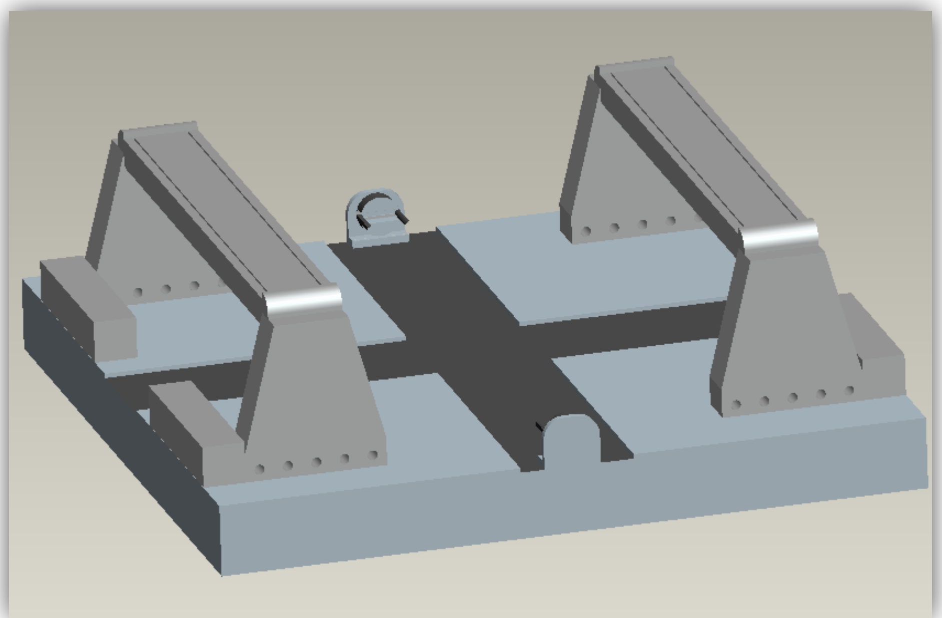


Figure. 4.10: Overview and Layout of a desktop machine cell.

4.4.2.2 Design Assessment and Analysis

Assessment analysis includes two supports to be fixed onto the base. This resulted in generating a MESH as in (fig. 4.11). Next, the first four natural frequencies were considered for analysis as follows:

1st natural frequency: 692.4 Hz 2nd natural frequency: 1101.7 Hz

3rd natural frequency: 1112.5 Hz 4th natural frequency: 1990.0 Hz

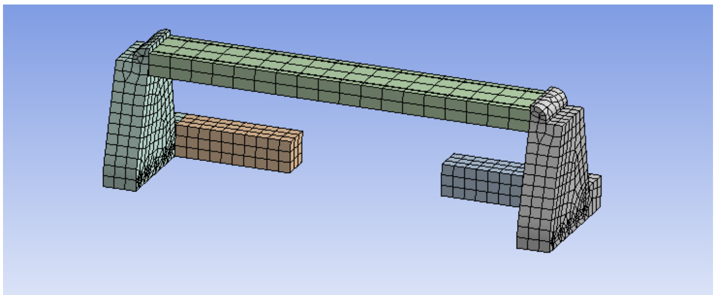


Figure 4.11: Generated Mesh of the gantry structure.

A convergence process is considered to ensure that the mesh is adequate enough to obtain the accurate results. This process includes increasing the number of attributes in order to generate more detailed Mesh before performing static and dynamic analysis. In this concept, the generated nodes of the Mesh have been increased from 11234 up to 167301. The 1st natural frequency only changes from 694 Hz to 692 Hz. This proves that the Mesh model is very accurate and capable of providing trustworthy results in the study (fig. 4.12).

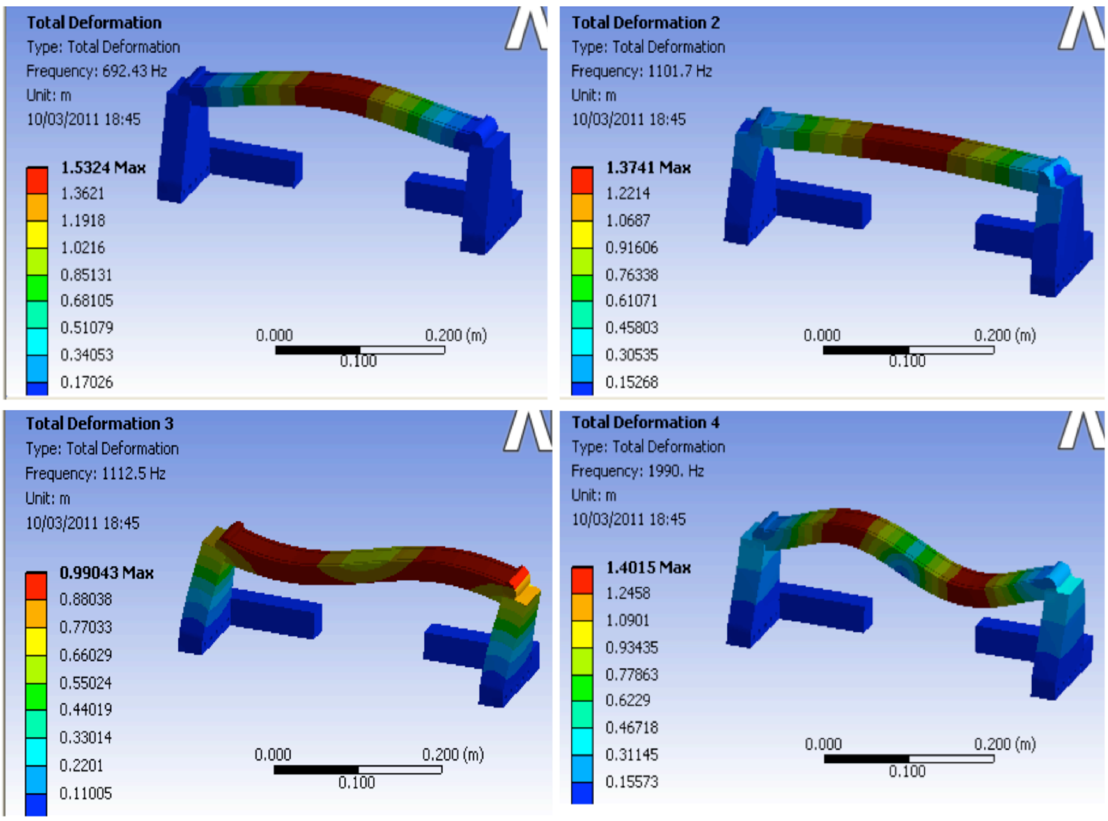


Figure 4.12: Four Natural Frequencies of the gantry structure.

In order to produce a static load analysis for this concept, a force of 500 N is applied downward on the top surface of the gantry. The maximum deformation observed is 34 um vertically. The middle beam that connects the side supports is shown to be too long and weak to support this amount of force. Therefore, when the same area was loaded with 50 N the deformation was 3.4 um which indicates the linearity of the structure.

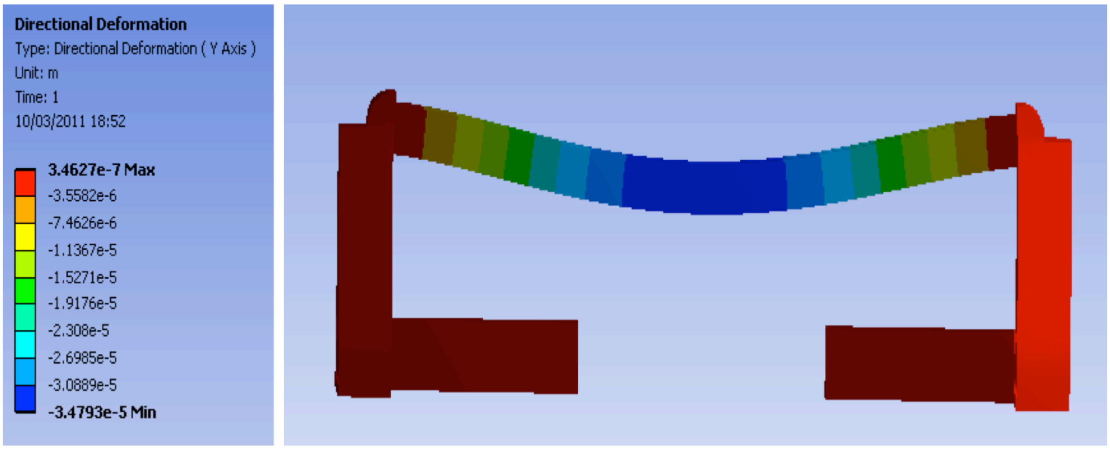
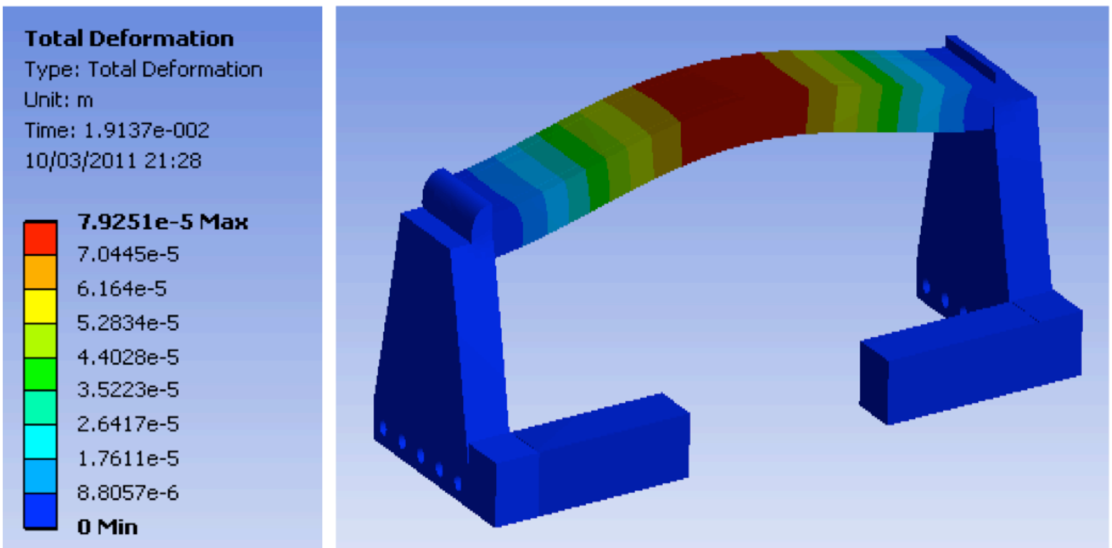


Figure 4.13: Deformation of the gantry structure in a static load mode.

When performing a Dynamic Load Analysis, the applied force was 50 N with natural frequency of 692.42 Hz on the top face of the guide way. The selection of this frequency was significant since it represents the fundamental natural frequency of the structure. Testing the structure by modelling this frequency will ensure a maximum excitation and deformation which is suitable to evaluate the performance of the structure.



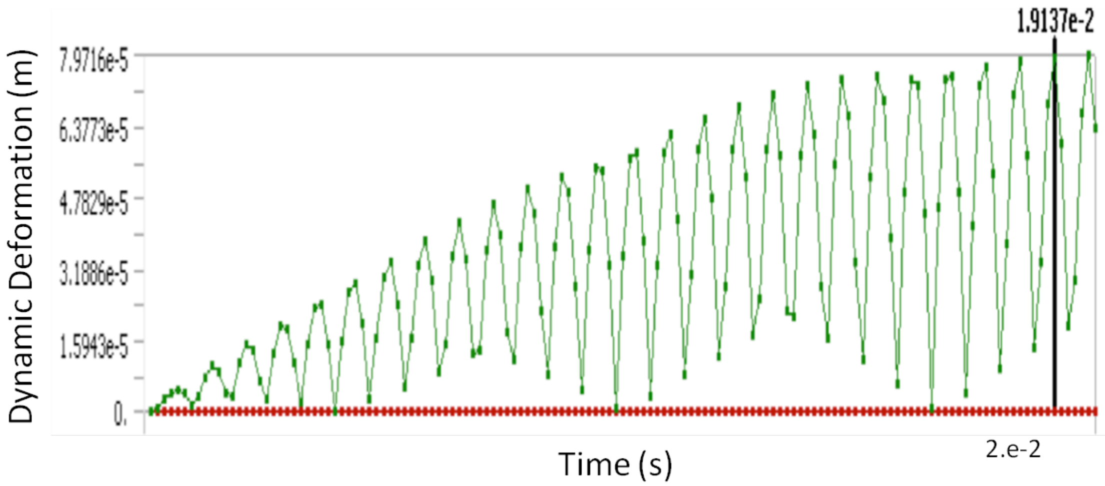


Figure 4.14: Deformation of the gantry structure under dynamic loading conditions.

In order to perform this analysis, the two supporters are fixed to the base in a surface-to-surface fixation mode, which provide more stability and contact between components. The maximum deformation is measured to be 79.7 um as represented in fig. 4.14. This analysis indicates that the design is weak and will perform poorly when a significant amount of force is applied. This is shown in the above reading as the transient responce (vibration) over the time reaches only 7.9716 to the power of (-5) before shifting into a constant forced vibration.

4.4.2.3 Design Limitations

Compared to the first concept, this desktop machine has achieved a considerable reduction in footprint. However, this modification has resulted in decreasing the level of flexibility of the system by having two fixed modules. Considering the high number of machining processes that can be performed, this approach indicates a limited level of upgradability in the future due to the fixing of both modules to the base of the structure. Also, The FEA model of this design shows low stiffness of the gantry structure, which means it is unlikely to achieve a satisfying level of machining accuracy due to the high level of deformation (up to 80 um), which eventually can certainly affect the surface finish, overall quality and the dimension accuracy of the components.

4.4.3 Design Iteration 3: Single-Structure Desktop Machine

4.4.3.1 Overview

This desktop machine concept has received a further reduction in footprint with a single machining module located in the centre of the system. Four machining tool heads are fixed to the inside of a rectangular structure creating a work envelope with a capacity of 150 mm L, 100 mm W and 75 mm H. Supporting units include two flipping stations located on the side of the base and two conveyor belts transferring machined parts around the –processing area- work envelope (fig. 4.15 – 4.16).

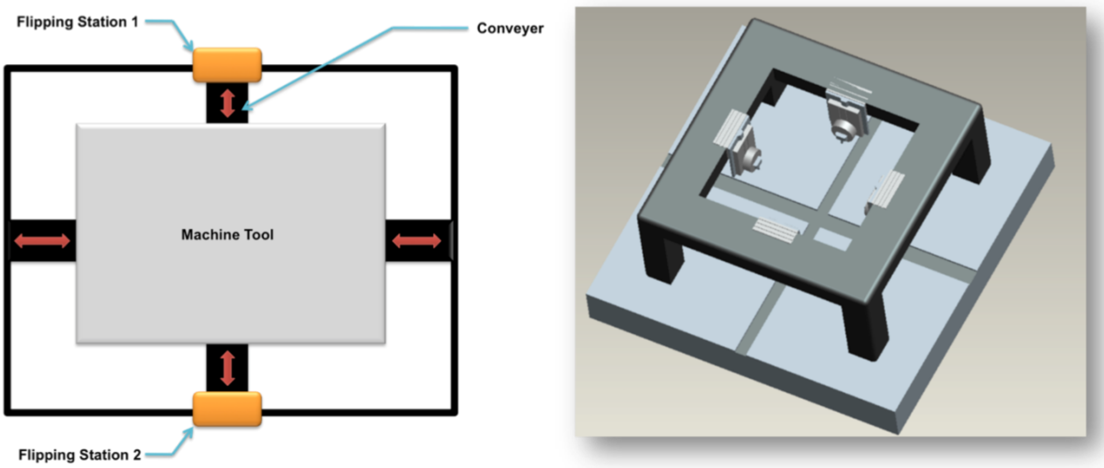


Figure 4.15: Layout of a single structure machine cell.

Such a concept demonstrates key features of miniaturised desktop machines including high portability and compactness. However, implementing this design will mean the need to replace it in the future due to the lack of flexibility and upgradability. Limited flexibility can be shown in the single solid structure that contains all machining modules.

This structure provides limited machining flexibility (Degrees-of-Freedoms) and in order to perform a new range of machining processes it can only be upgraded by re-designing the entire structure. Such a short life-span concept can be used as a sub-system that is dedicated to perform specific standard machining processes rather than a reconfigurable micro-machining system.

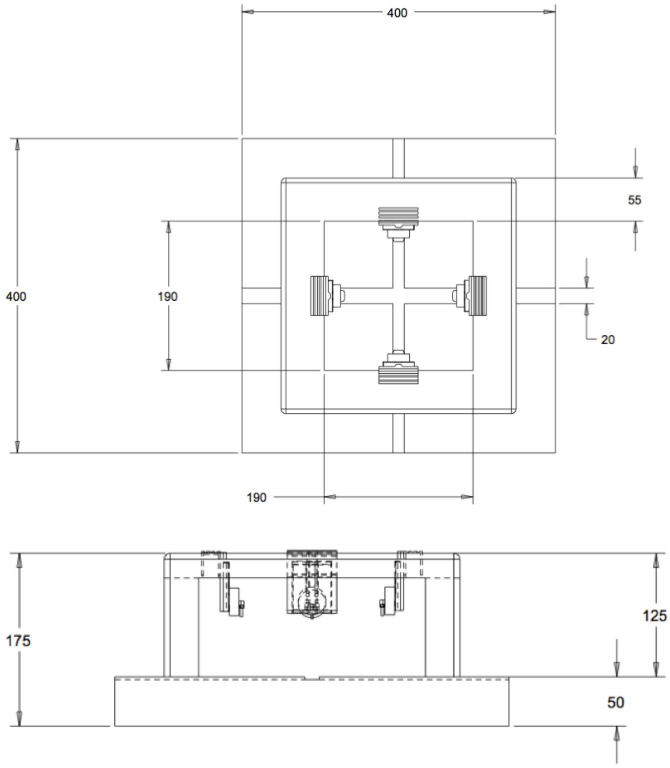


Figure 4.16: Design size and footprint of a single structure machine cell (in mm).

4.4.3.2 Design Assessment and Analysis

This concept has a uniform and neat Mesh model due to employing a rectangular design with many symmetrical features as shown in fig. 4.17. Also, it shows the effect of designing the entire structure as a single-machined unit, which minimises the vibration that may result from connecting several parts (supports) to the main structure (square frame).

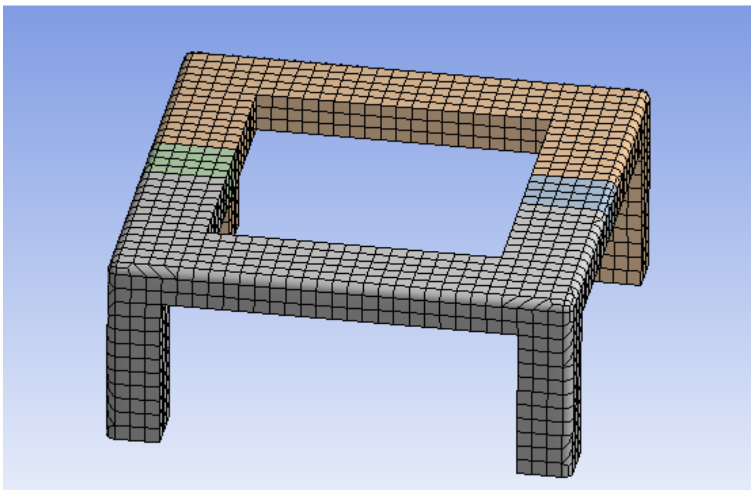


Figure 4.17: Generated Mesh of a single-structure desktop machine.

The first four natural frequencies of this design are shown below. These results were achieved by including a single boundary condition, which is the fixation of the four supports to the granite base.

1^{st} natural frequency: 841.15 Hz 2^{nd} natural frequency: 853.11 Hz

3^{rd} natural frequency: 1141.9 Hz 4^{th} natural frequency: 1344.9 Hz

The reason why the 1^{st} and 2^{nd} natural frequencies have a similar value is due to the design's symmetry. In order to calculate the static load of the structure, the force was applied directly onto the middle part of the left top face where it is attached by a spindle. The reason for applying -500 N vertically on this face is because of the weight of the spindle and the cutting force generated during the manufacturing process. The maximum deformation was about 9.47 um vertically as shown at below Fig. 4.18. All four areas have been put under force to calculate the deformation; all forces have developed the same response by giving the same value. This was due to the identical geometry, material and force applied in each one of the four cases.

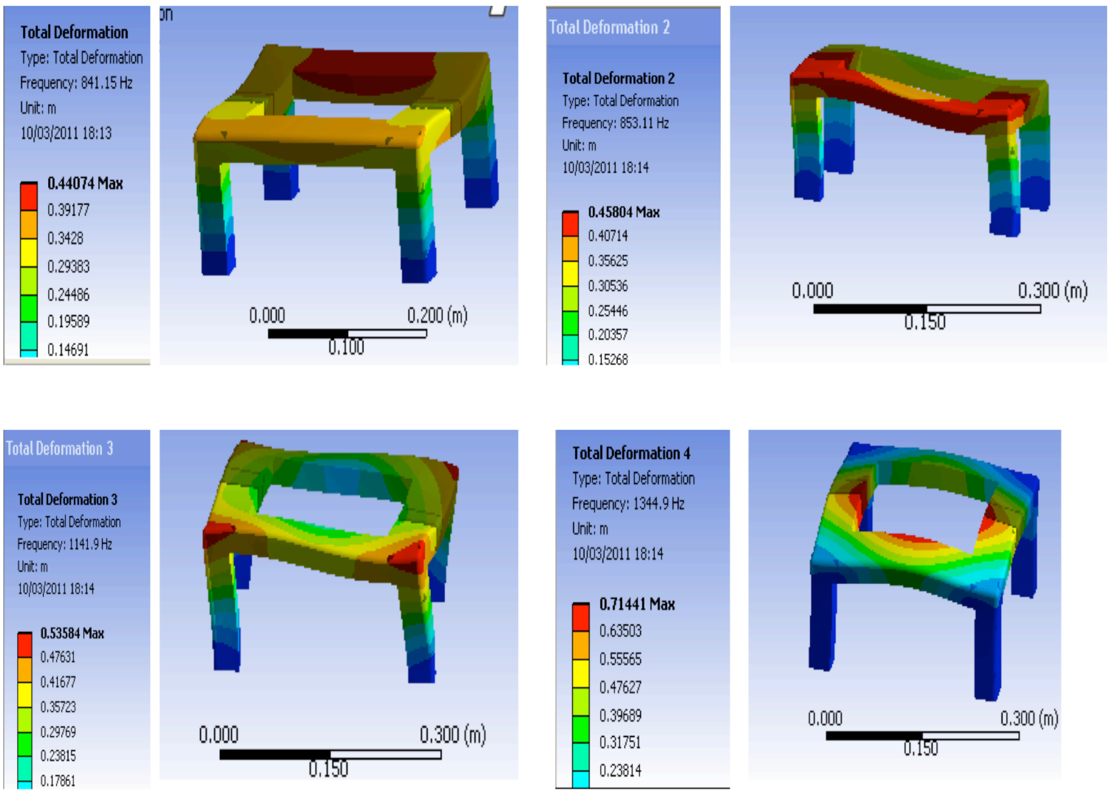


Figure 4.18: Four Natural Frequencies of the gantry structure.

The dynamic response of this concept can be calculated by applying a force of 50 N with driving frequency of 1491 Hz. The four supports are fixed to the base and all machining tool-heads are running. The simulation resulted in a maximum deformation of 5.63 µm (fig. 4.19).

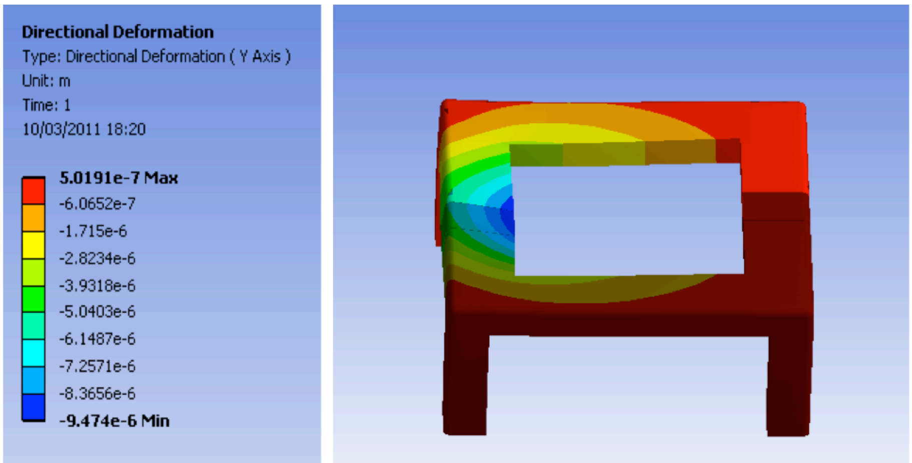


Figure 4.19: Deformation of the frame structure in a dynamic load mode.

These results show that the transient vibration happens initially but it fades out representing the initial vibration of the structure; then it reaches a point where it can only be generated by applying another force, which will generate a new series of vibrations (forced vibration) as in fig. 4.20. This graph indicates improvement in the rigidity of the structure compared to the previous two design iterations. This is due to the decrease in the design's dynamic deformation by reaching a value of 5.63 µm.

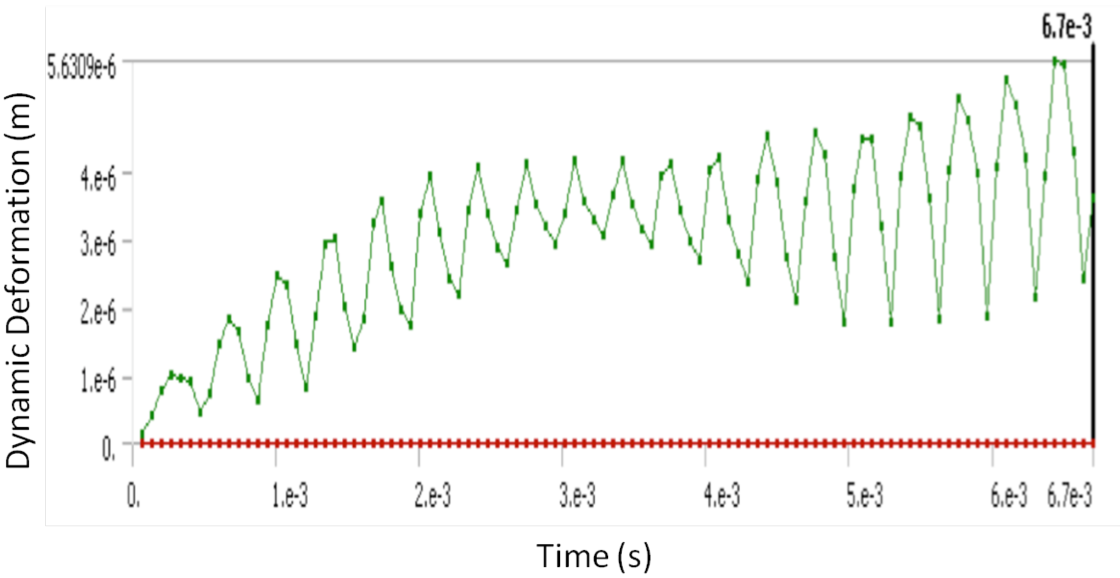


Figure 4.20: Transient response of the structure over time.

Based on both static and dynamic response analysis, the main disadvantage of this design is that during any machining process, each machine tool-head is considered as an excitation point and vibration source due to the generated vibration, which means that these tool-heads are affecting the static stability of the structure and the dynamic performance of the system. The reason for this limitation can be traced directly to the design of the frame structure, which allows physical contact between one frame and another. Therefore, a possible design optimisation can be to avoid physical contact between any numbers of processing modules within the system in order to reduce the level of vibration that is generated during machining.

4.4.4 Design Iteration 4: Four-Modules Micro-Machining Centre

4.4.4.1 Overview

The design process of this concept started with designing a robust, small footprint base (fig. 4.21) for a micro-machining centre, with at least four machining modules fixed individually on top of the base. This approach focuses on increasing the level of modularity within the system, which can be done by implementing a plug-and-play concept for all four machining modules.

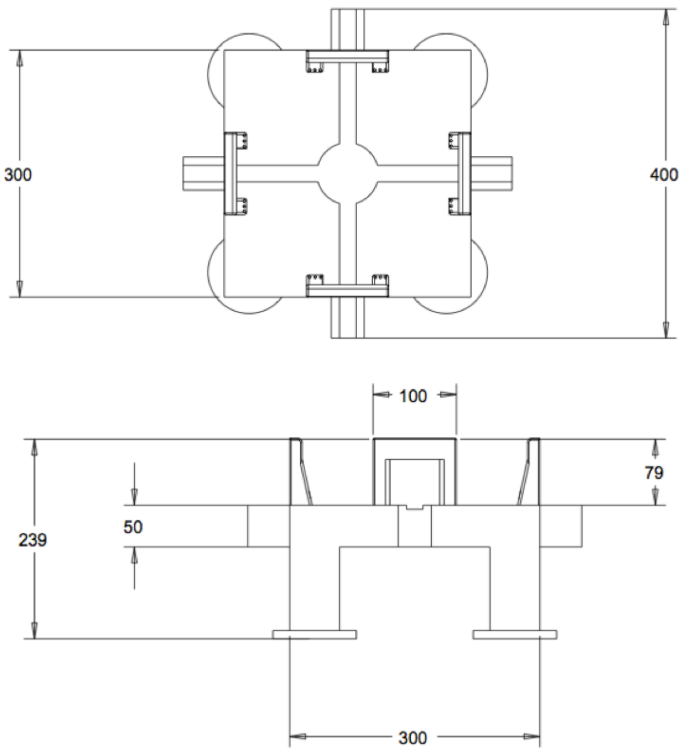


Figure 4.21: Layout and footprint of the fourth concept of a machine centre in (mm).

These design characteristics will provide the system with more flexibility to perform any required machining process by designing the module and fixing it on top of the base. Furthermore, compared to the previous concept (3rd Concept), having all four modules fixed individually on the base will reduce the vibration resulting from performing four machining processes simultaneously due to the lack of direct physical contact between the four structures (fig. 4.22).

However, it has been noticed that the identical design, fastening techniques and the assembly method of these modules resulted in compromising the overall stability of the system. Such a problem can be corrected by re-designing each module before running any analysis to test the performance of both static and dynamic structures. This process involves geometry optimisation, structure analysis and machining simulation. Also, to develop a valid and more practical analysis model, each part of this concept must be tested and analysed separately in order to observe the performance of each part. Therefore, two sets of analysis will be performed. The first set will focus on developing a static and dynamic analysis for the base, while the second set will assess the performance of the frame structure that holds the tool-head and the other mechanical components.

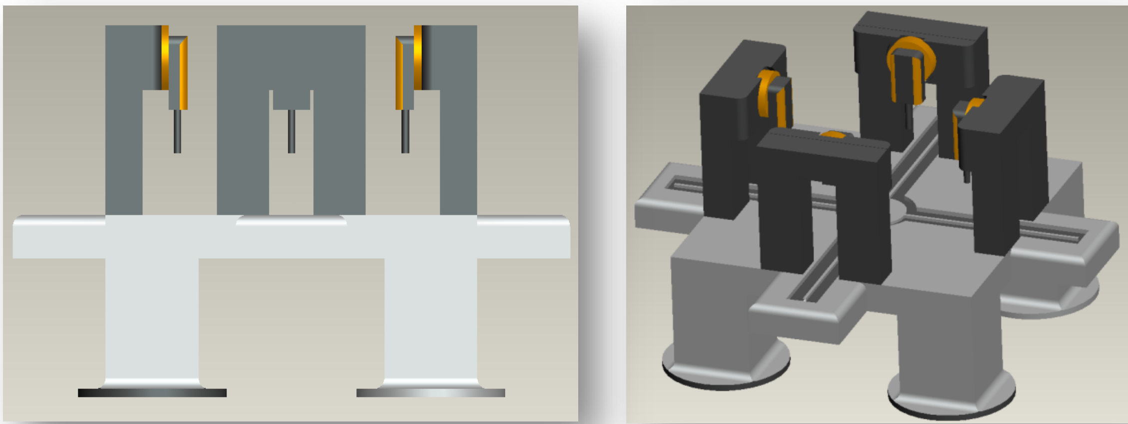


Figure 4.22: Overview of the machine centre

The mesh of the model is shown below (fig. 4.23). The Hex mesh gives more accurate results by indicating the structure has a uniform design, which resulted in a harmonised Mesh. However, the centre of the base where a rotary distribution tray is placed to dispense machined parts around the system is showing a sort of deformation caused by having several design features such as sharp angles, round edges and level dissimilarity.

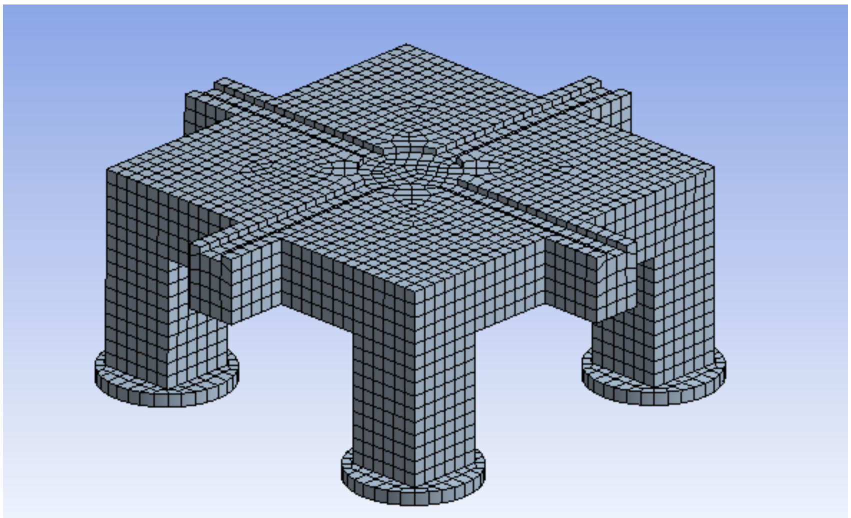


Figure 4.23: Generated Mesh of the base.

The first four natural frequencies and mode shapes are:

1st natural frequency: 1215.6 Hz

2nd natural frequency: 1216 Hz

3rd natural frequency: 608.2 Hz

4th natural frequency: 2089.1 Hz

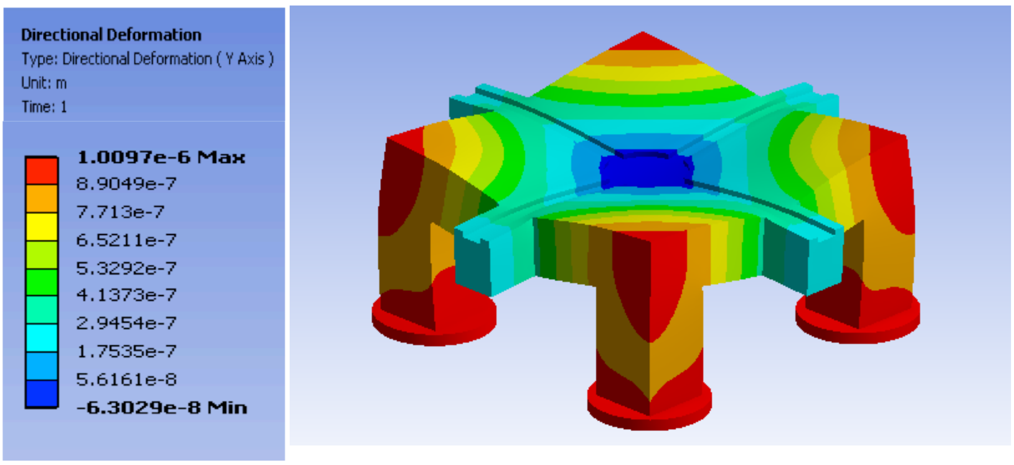


Figure 4.24: Deformation of the base structure in a static load mode.

Applying a downward 500N force on the top slot surface resulted in generating a static deformation of 0.475 um (fig. 4.24). Following the previous methodology, studying the dynamic load of the base required applying a force of 50 N with excitation frequency of 2089.1 Hz on the centre of the base. The maximum deformation generated was 1 um as shown in fig. 4.25. Both results from the static and dynamic analysis presented a valid design for a base that can be used in micro-manufacturing systems. The rationale is shown in the structural performance of the base represented in the small amount of deflections and excitations when forces were applied. Compared to previous base designs in this project, the thickness and geometry of the supports can be considered as key design features in reaching this level of performance.

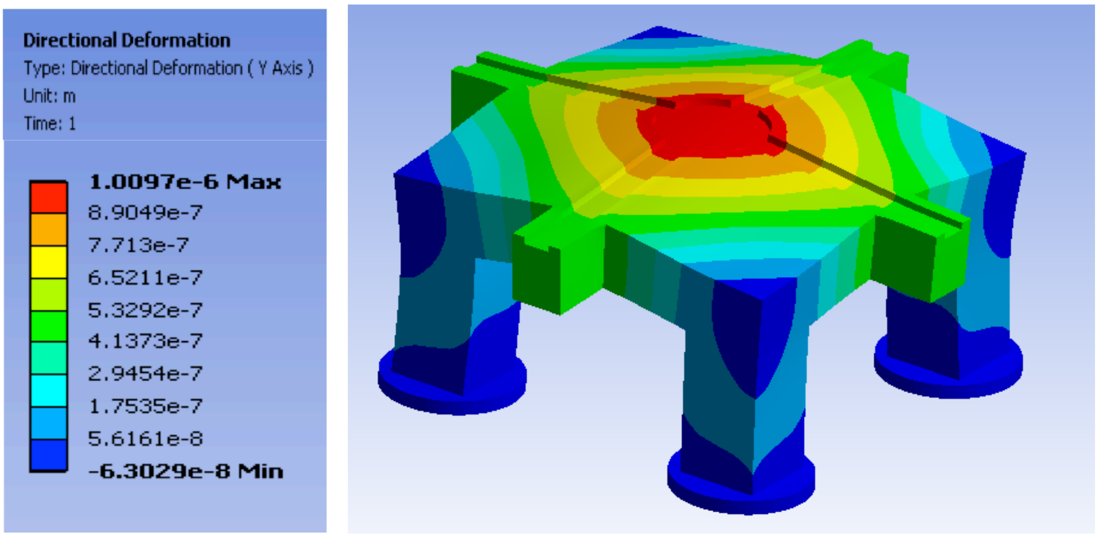


Figure 4.25: Deformation of the base structure in a dynamic load mode.

Similar design assessment methodology will be performed on the second part of this system. First, a Mesh model is developed from the frame structure to show several surface deformations causing variations in features and geometry. Also, including cavity for fastening purposes increased the level of deformation in the bottom of the frame structure as shown in fig. 4.26. The static analysis by applying -500 N on the top surface of the gantry, showed a static deformation of 2.68 um as in Fig. 4.27. However, it implies that the applied load affects the two contact surfaces between the supports of the gantry and granite base. Therefore, changing the gantry's geometries must be considered in the next design iteration in order to minimise the applied pressure of the supports.

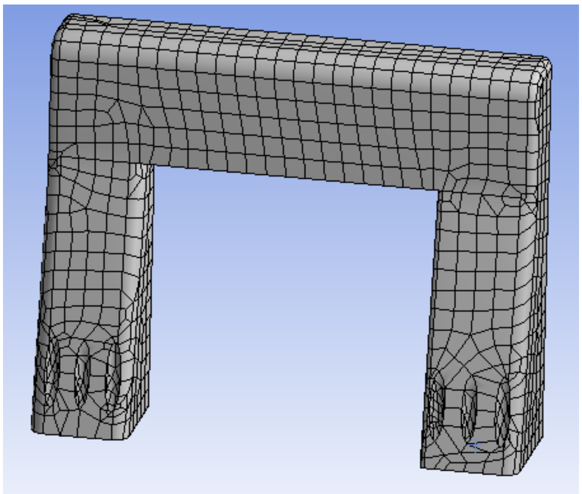


Figure 4.26: Generated MESH of the frame.

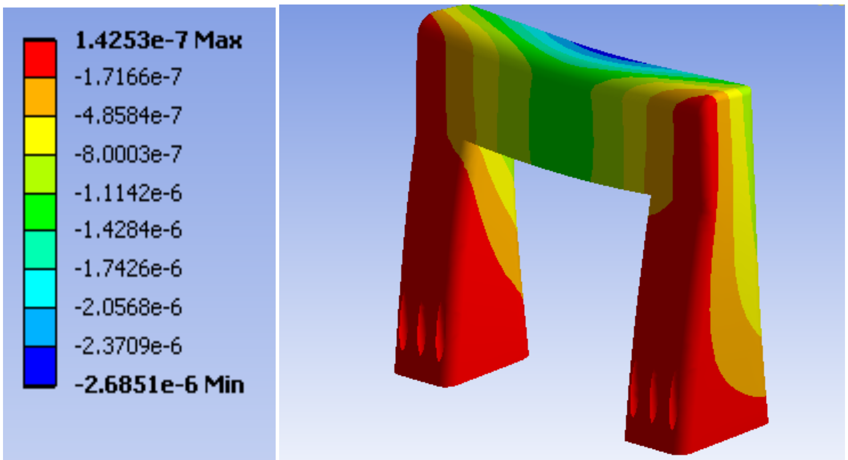


Figure 4.27: Deformation of the frame structure in a static load mode.

The first four frequencies are shown in the Figure.

1st natural frequency: 2126.5 Hz

2nd natural frequency: 3304.3Hz

3rd natural frequency: 3915.2 Hz

4th natural frequency: 8384.1Hz

The disadvantage of this design is that both the base and the gantry are deformed when performing as a system. The gantry is more rigid in Y direction than X direction. However, tool-heads including spindles are applying a significant load on the frame in both static and dynamic modes. As a result of this, during any machining process (drilling or milling), the bending moment will be induced, causing a significant deformation on the gantry.

Dynamic analysis: Apply 50 N with a driving frequency of 8943.8 KHz. The dynamic deformation is 3.7 um along the vertical direction as in (fig. 4.28) showing better performance compared to the previous three design iterations.

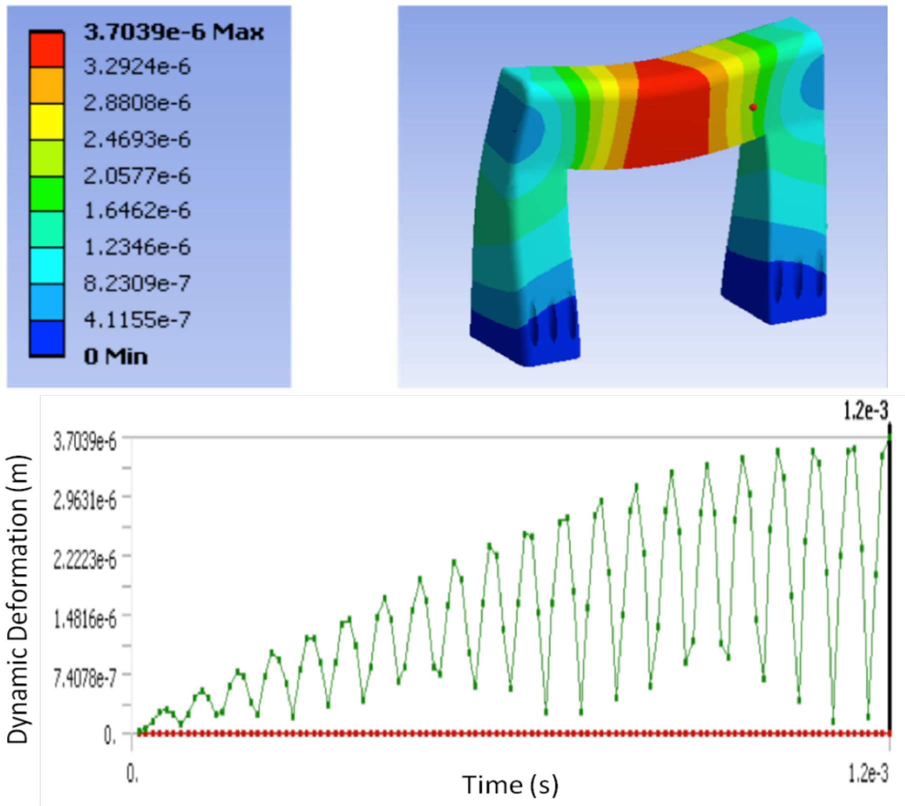


Figure 4.28: Deformation and Transient response of the structure over time.

Based on the previous theoretical designs to develop a novel design, the limitations of each idea had to be resolved where any design advantage needs to be considered and included in the final conceptual design. Therefore, after reviewing each one of the previous concepts individually, a new design representing a final concept has been developed. Based on several design and performance assessments, key features will be selected from the table and will be implemented in the final design of the Reconfigurable Micro-machining cell.

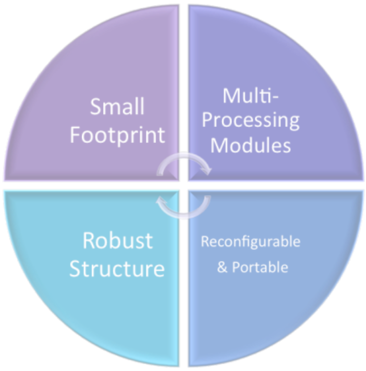
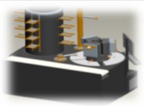
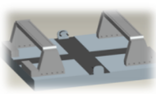
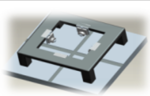


Figure 4.29: Acquired features from all four concepts.

The following table (4-1) highlights the advantages and limitations of each one of the previously reviewed concepts based on the relativity to pre-determined design criteria. Based on this, a new conceptual design will be developed following the iterative design methodology using criteria from (fig. 4.29) and table 4-1 as qualitative criteria.

Table 4.1 - Design criteria assessment.

	Re-configurability	Size / Portability	System integration	Structural performance	Upgradability
	+	-	+	-	0
	+	+	0	-	0
	0	+	-	-	-
	0	+	-	+	0

(+) Good (-) Poor (0) Fair

4.4.5 Design Iteration 5: Reconfigurable Micro-Manufacturing Cell

4.4.5.1 Overview

In this project, the proposed design of the micro manufacturing cell (Fig. 4.30) consists of several main components. Flexibility and re-configurability have been considered during each stage of developing each component within the cell. There are two sets of modules attached to the granite base (Al-Sharif et al, 2011).

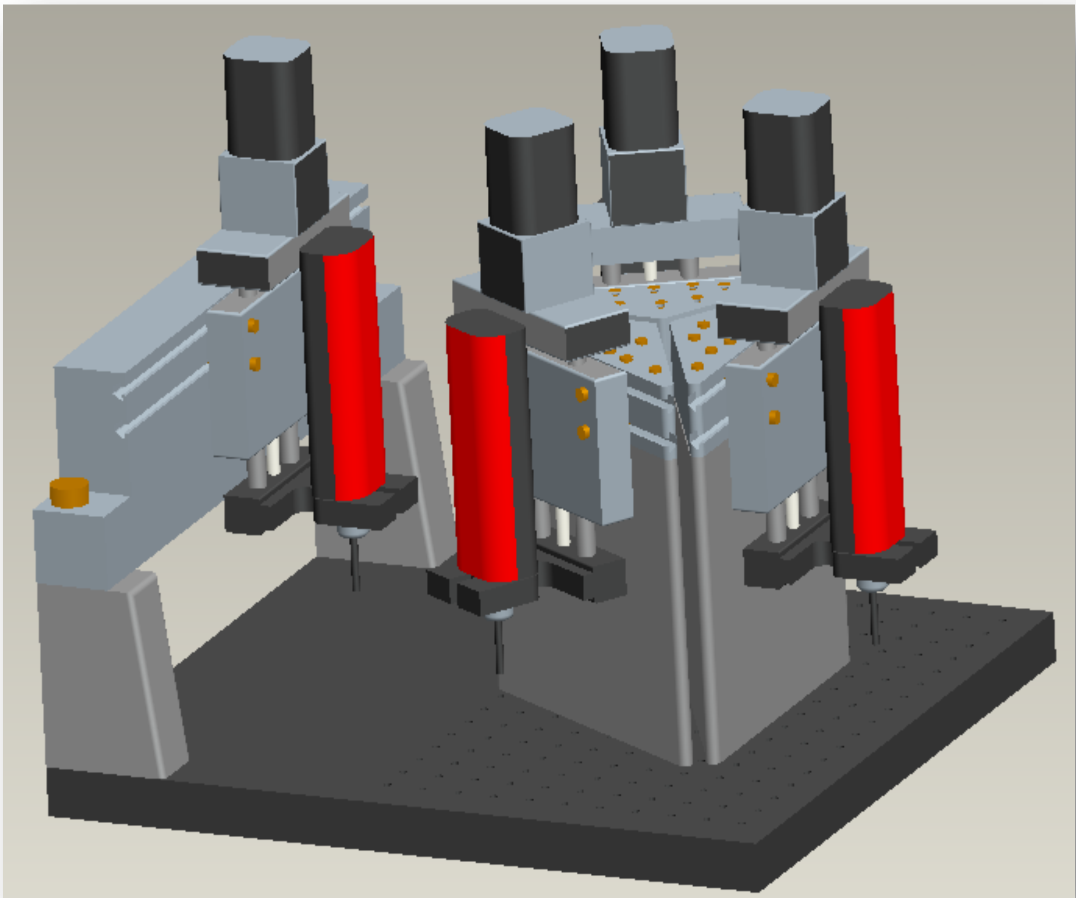


Figure 4.30: Overview of the resulted design iteration.

The first module is a fixed gantry structure, which is used as a base for performing several machining processes based on the requirements of the end product including a fixed module within the system. This is aimed at delivering a number of design criteria including upgradability. This feature can be considered in this design by attaching new machine tools into the system to the fixed parts. For example, the two supports of the gantry structure can be used as a base for a lathe machine, which adds to the turning process of the list of machining processes that can be performed by the system.

The second part is a reconfigurable hexagonal module, which consists of three identical units. Each unit has a triangular shape profile providing the required flexibility to have more than one configuration. All parts are fitted on top of the granite base within a small footprint, providing the entire cell with a high level of portability and mobility.

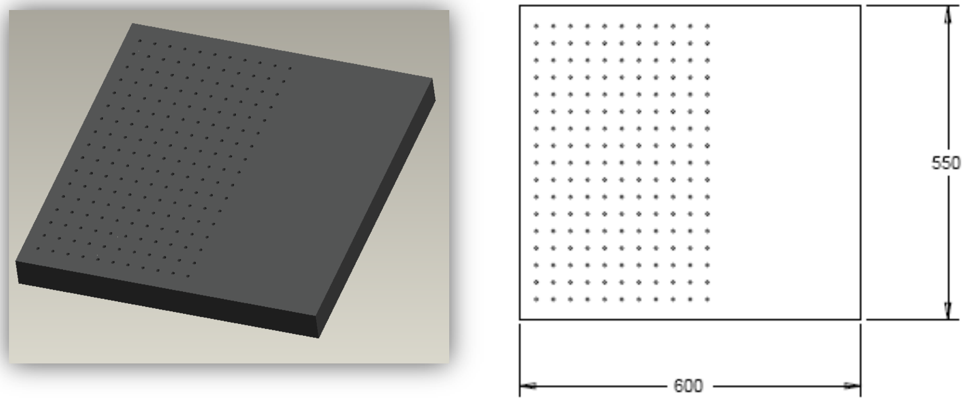


Figure 4.31: Layout of the granite base (in mm).

The following section will describe each component above in detail, justifying its design, material selection and applications within the micro-manufacturing cell.

4.4.5.2 Granite Base

The granite base has been designed to accommodate a wide range of components within a small footprint (Fig. 4.31). Nevertheless, having several processing modules fixed to the base and operating simultaneously can compromise the stability of the system and the accuracy level of each machining process. Therefore, the aim was to build a robust base that can deliver the required level of vibration isolation and stiffness.

In this project, the base represents the full footprint of the micro manufacturing cell, with dimensions of 600 mm (L), 550 mm (W) and 50 mm (h). Also, 60% of the base's area was machined to contain 187 screwed holes with a size of M6, creating an 11 X 17 grid of holes. The purpose of such a design is to provide the flexibility of fixing any required components and modules to several locations on the base.

4.4.5.3 Hexagonal Module Structure

This part of the cell consists of three identical components that can be attached to the previously mentioned granite base in several configurations. Each module of the three has a triangular shape with machined edges and ends. These modules work in collaboration to manipulate and machine each work piece in the system.

In addition, the module was designed to perform a number of high-precision machining processes to produce high-quality products. Several design criteria have been considered, including enabling tool heads to be replaced quickly in order to reduce the required set-up and production time. Furthermore, the entire module is designed to be rigid and stable enough to deliver the required level of precision and performance. These issues represent major design challenges.

The assembled shape is hexagonal with granite as the material of choice. The selection of Granite was based on its advantages when it was used in designing the first design iteration in this research in addition to it being suitable for building machine centres. The hexagonal shape allows fitting a different processing head into each module. Each processing head faces a different direction. Hence, any physical contact or interference between the processing heads whilst in operation is avoided. This is especially important during any assembly or inspection processes (fig. 4.32).

Another issue that has been considered during the design process of this structure was connecting each module to the granite base in a flexible and efficient way. In order to achieve that, each end of the triangular-shape module was designed to include ten fixation points. Each point is represented as a hole with a size of M6 screw in order to match the size of the base's holes.

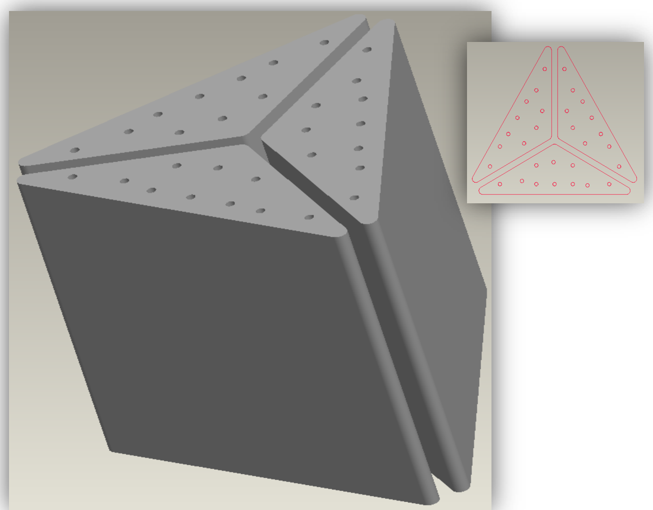


Figure 4.32: Design and layout of the hexagonal module.

Also, the vertical edges of each module have been machined to have a round shape instead of sharp edges. This modification has a massive effect on how the structure will react to vibrations during any machining process as will be shown in following sections.

The dimensions of the module are 250 mm (h), 240 mm (L) and 80 mm (w). Due to the size of each part, the system can process work pieces within a work envelope of 120 mm (L), 80 mm (w) and 100 mm (h).

4.4.5.4 Gantry Structure

Another part of the system is a processing module, which has a different design, aimed at providing more flexibility to the system by performing more machining processes within the small footprint of the base. This design feature is significant since it provides a potential solution for the system to cope with any manufacturing demand in the feature that may require a modification in the system structure, layout or configuration.

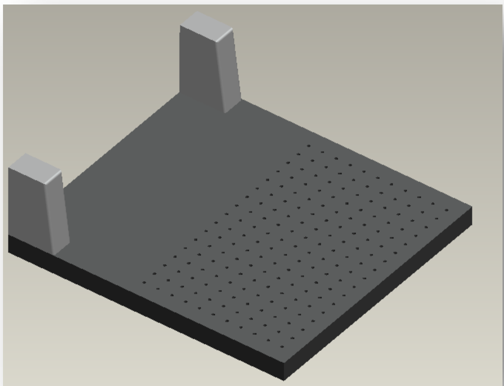


Figure 4.33: Two gantry supports attached to the base.

This structure (Fig. 4.33) consists of two identical support units. Both of them were made out of granite and fixed directly to the base in a permanent stationary position.

Also, the stiffness of the granite structure allows adding standard machining components when both parts are connected to each other by metal components (steel, aluminium etc..) creating a wide range of gantry structures based on the requirements of each machining process. Each one of the two components has the following dimensions; 95 mm (L), 50 mm (w) and 150 mm (h) (Fig. 4.34). Furthermore, to ensure the stability of this design, both units are made out of granite. Also, the shape has several features including machine-rounded edges to reduce vibration, and the area of the base in each unit is larger than the top-end in order to provide more support to the entire structure.

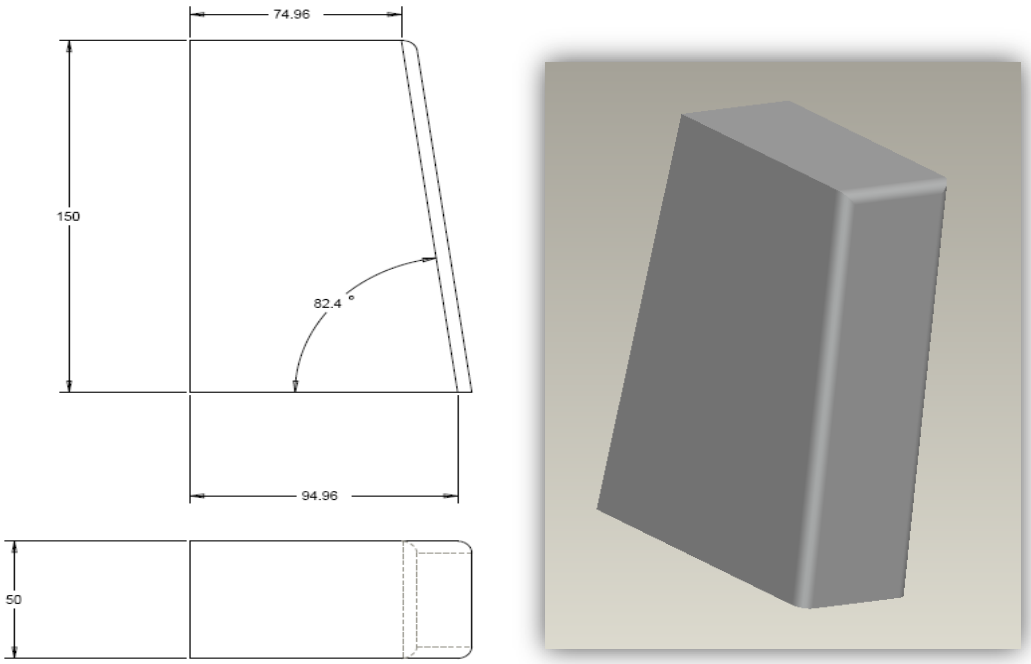


Figure 34: Dimensions of a gantry support (in mm).

4.4.5.5 Prototype Production and Costs

In order to build a prototype that is capable of demonstrating the concept of the proposed architecture, a production approach has been followed in order to ensure building the prototype within a specific budget and schedule. Due to the need to build several parts within the cell using high precision granite, the cost and fabrication process of making each part must be considered. This type of granite needs to be made using casting moulds, and different parts require separate moulds. Therefore, in order to reduce the cost of the prototype, reducing the required number of moulds was considered during the design process. This can be achieved by designing a single mould for each family part within the system. This approach can be shown in the design of the gantry supports and hexagonal module (fig. 4.35).

A single casting mould has been used to create both gantry support units, which was made possible due to the identical design of both units. Also, a similar process is used to produce each triangular part in the hexagonal module.

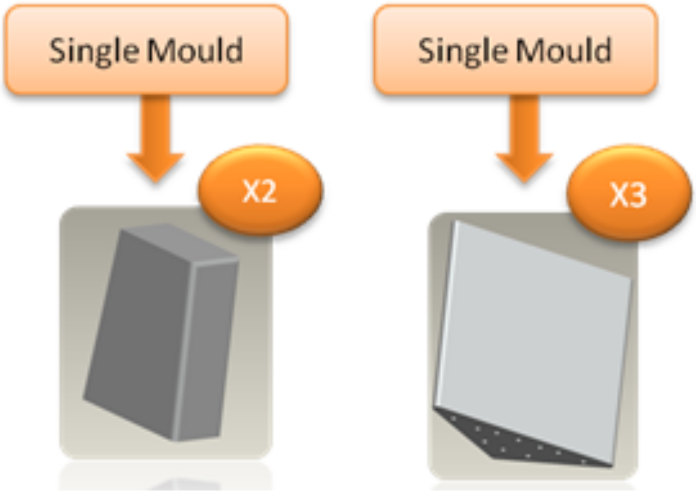


Figure 4.35: Single mould to create several units.

4.4.5.6 Re-configurability and Process Planning

Modular structure and reconfiguration are required for micro manufacturing in the current market climate where variations of micro products occur at shorter and shorter intervals. Modularity is one solution for micro manufacturing systems to outlive the products they were originally designed for where the cell is designed to act as a modular system, as the manufacturer can easily configure the platform and later reconfigure it to meet customer‘s future needs.

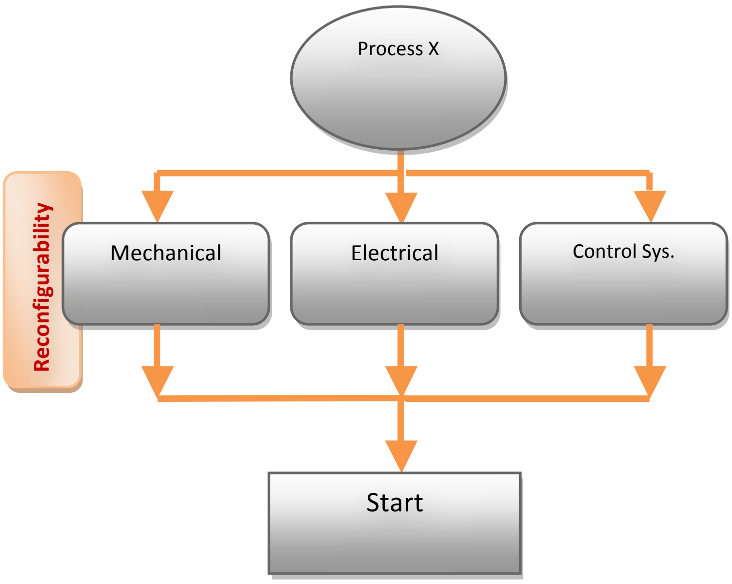


Figure 4.36: Process re-configurability within a system.

Modularity is also a cost-efficient solution, and makes later upgrades or modifications to the platform easier. The manufacturers can therefore respond to customers or other market changes rapidly without building or buying new machines. However, when it comes to reconfigurability, there are three levels that need to be fulfilled in order to come up with a reconfigurable structure. These include: Electrical, Mechanical and Control system re-configurability (fig. 4.36).

Mechanical reconfigurability provides the capability of the system to comprise a wide range of mechanical components such as linear stages, tool tips and spindles. While electrical reconfigurability means the ability of the system to adapt with motors and amplifiers based on the requirements of each end product and machining process. Finally, control systems need to be reconfigured by selecting suitable software modules to perform any required process as the selected types of electrical components influence this configuration.

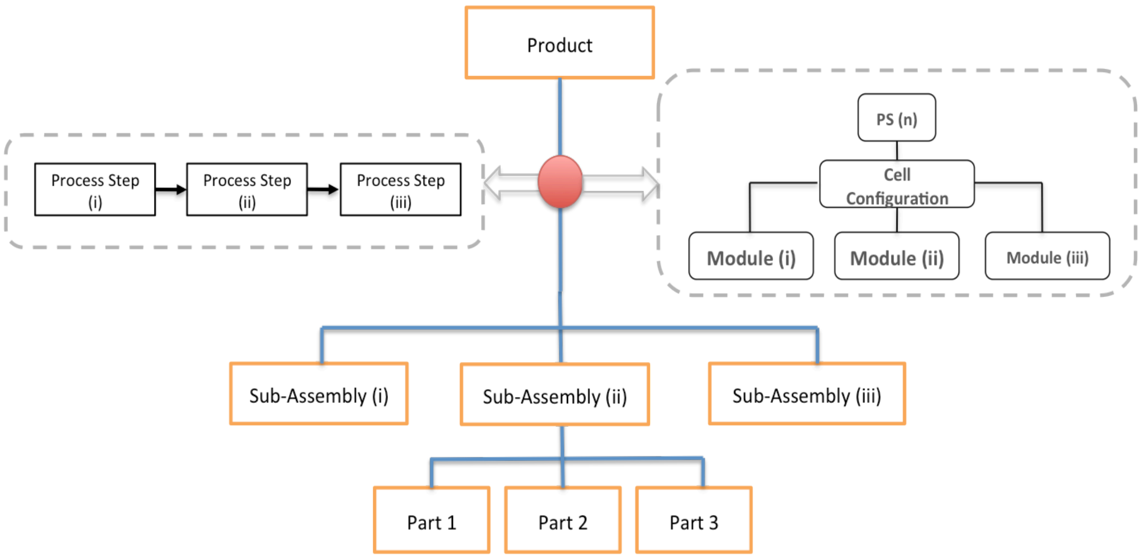


Figure. 4.37: Linking BOM /BOP and RMC configuration.

Another type of re-configurability that has been considered during the design process of this system is based on the Manufacturing Process Plan (MPP), which was reviewed earlier in chapter 2 and considered as one of the design assessment criteria. This consideration includes developing a design flexibility to reconfigure the Bill-Of-Materials (BOM) and Bill-of-Process (BOP) of the system based on the machining requirements of the machined part (end product). Therefore, two levels of flexibility can be added to the system; structural level and process level (BOP). Both types are determined by the pre-defined specifications of the product. To specify, the structural re-configuration involves changing the cell's layout and machining zone to provide the required space and machine tool orientation for each product. The process level is shown by re-configuring the Bill-Of-Materials (BOM) and structure as in figure (4.37). Furthermore, each component has been designed to provide the RMC with a level of flexibility and re-configurability. This section will discuss the flexibility and reconfiguration of the cell structure based on implementing manufacturing strategies such as Cellular Manufacturing (CM) and design scalability as reviewed in previous chapters.

4.4.5.7 RMC Layout and Cellular Manufacturing (CM)

CM is implemented within the proposed design as part of the reconfiguration characteristics of the RMC. This implementation aims at increasing the capability of the system to change its layout in order to achieve the required machining set-ups.

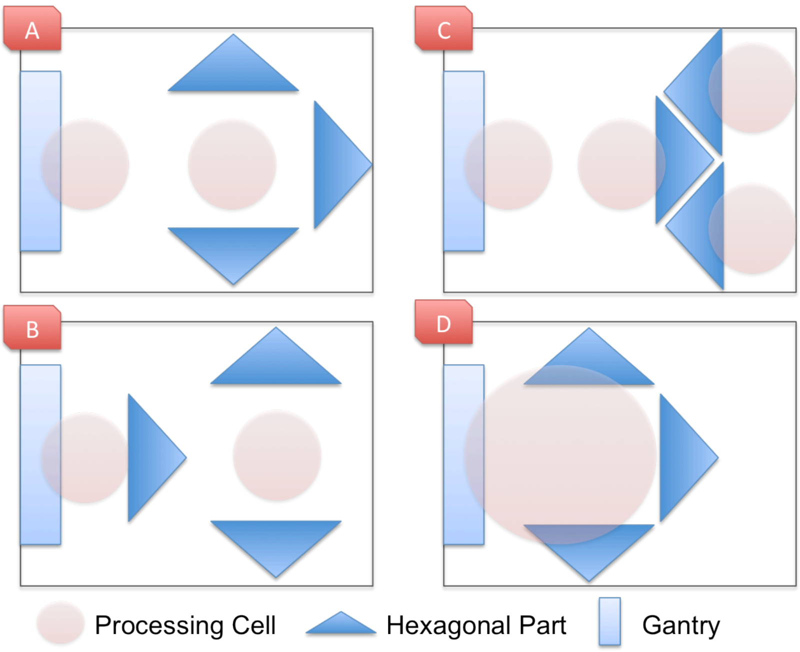


Figure 4.38: Examples of possible cell layouts.

As shown in the above figure (4.38), having several movable parts of the structure represented in the hexagonal structure parts allows changing the cell's layout. Each module can be considered as a single machining cell that is capable of performing a range of machining processes as in layout C. Layout A shows an arrangement of three modules facing each other to create a single machining cell which is able to perform three different processes on a single work piece, while the gantry module is fixed and considered as a single cell as well. Layout B suggests a second cellular arrangement as one of the modules is shifted closer to the gantry structure, developing a layout of two machining cells that machine two work pieces. Another possible configuration is shown in D, where all modules in the RMC are arranged to create a single machining cell.

The flexibility can be represented by the base through the ability to change the layout of the modules according to the requirements of the machining process and production plan (fig. 4.39). Changing the layout is made possible by the number of holes machined and the position of each hole. Each hole is screwed with a size M6 screw and is located 30 mm from the next hole, creating 0°, 45°, 90°, 135° and 180° angles. This configuration allows the connecting of modules to the base in various orientations. The purpose of having such a design feature is to achieve several layout designs capable of dealing with several part sizes and shapes. Also, it allows adapting to various process and production requirements such as installing new mechanical components and the achievement of high throughput production.

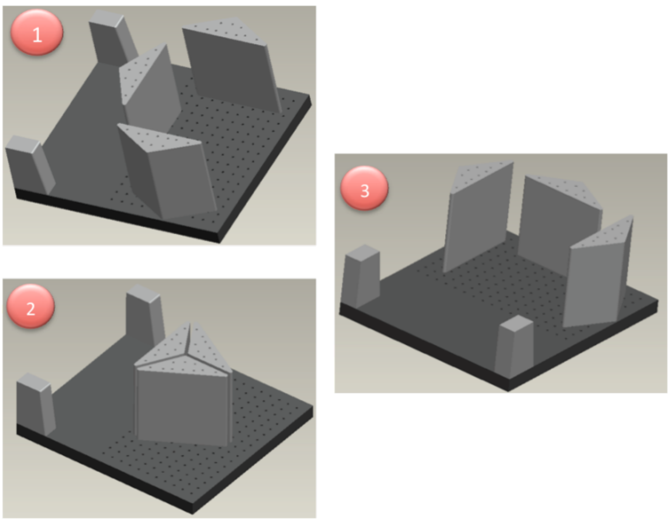


Figure 4.39: Reconfiguration of the RMC.

4.4.5.8 Hexagonal Structure

After increasing the flexibility of each triangular part in the hexagonal module required several design issues have been considered;

1. In order to fix each part to the base in different orientations, both faces of the part include a unique 10-hole design. Each hole has a specific location allowing at least 4 contact points (out of 10) to connect the part to the base in any given position. Furthermore, this arrangement helped significantly in reducing the cost of making this module, since it requires making one mould to create all three parts of the module instead of making three different moulds (fig. 4.40).

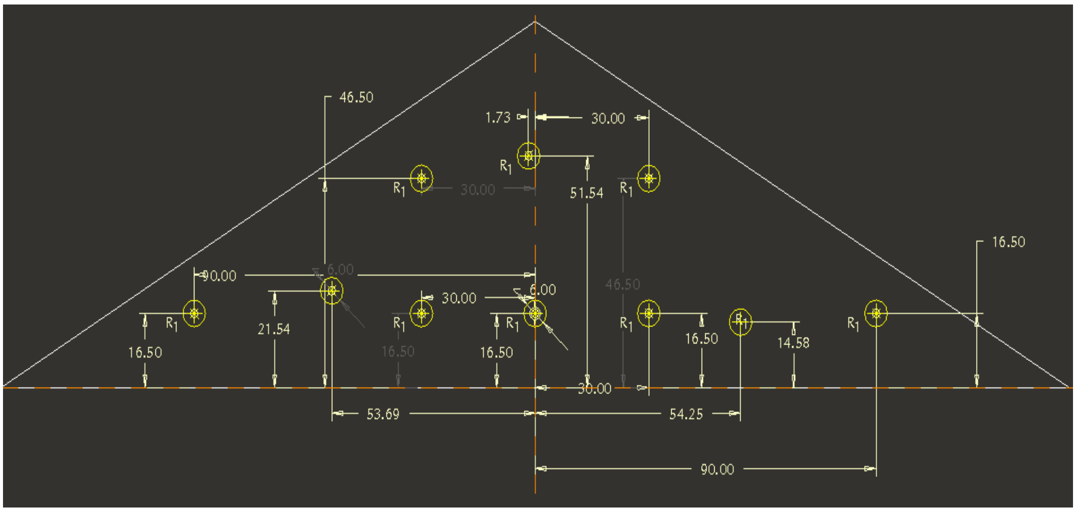


Figure 4.40: Detailed view of the position of each hole in the hexagonal module.

2. Machining both sides of the part allows using the same fastening method to attach this part to the granite base as well as attaching mechanical components to the top of the part.
3. Dimensions and overall size of parts in the hexagonal module allows fitting a wide-range of standard components including, high precision linear stages, rotary stages, machining tool and motors etc. This provides the module with a flexibility of having several configurations to hold, rotate and machine the work piece. Each work piece can be processed within a work envelope of 120 mm (L), 80 mm (w) and 100 mm (h) as shown in figure 4.41.

Based on the required machining process, a selection of machining axis can be configured (5 axes as a standard). This flexibility and degree of freedom (D.O.F) make it possible for any module within the cell to perform a 3D measuring and machining process. Even more axes and degrees of freedom can be added to the concept by including gantry, rotary or arch-type structure to the hexagonal module.

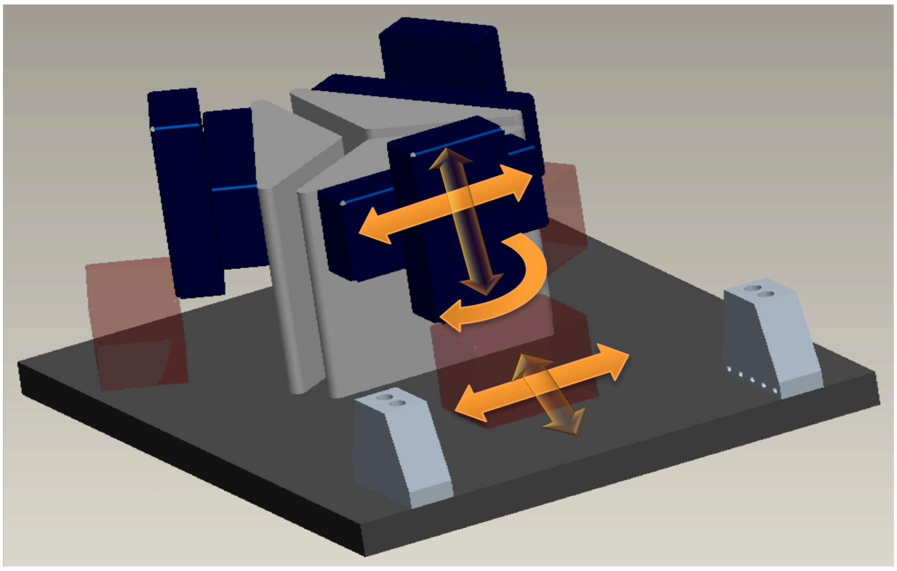


Figure 4.41: Work envelope and machining axes.

4.4.5.9 Gantry Structure

The gantry structure has several levels of reconfigurability including, process level, structure level and machining level. These levels can be demonstrated as follow:

The two granite support units of the gantry structure should be connected to each other using a metal frame (usually aluminium or steel). The flexibility of the design allows supports to be connected by a wide range of frames; these frames can have a single-gantry, double-gantry or even an arch-type gantry structure.

Since each machining process requires specific machine tools and work space and degrees of freedom, the design of the gantry structure provides the needed flexibility to perform these processes. Figure 4.42 shows three possible configurations of metal frames that can be attached to the structure in order to achieve a high level of flexibility. Part A represents a double gantry structure which allows use of both sides of the frame to perform two machining processes; using each part of the frame as a machine tool base. Part B has an arch-type frame connecting the two support units of the gantry to each other, this configuration is usually used to increase the machining flexibility of the structure by adding an extra degree of freedom. Additionally, Part C represents a typical gantry structure with a single-frame.

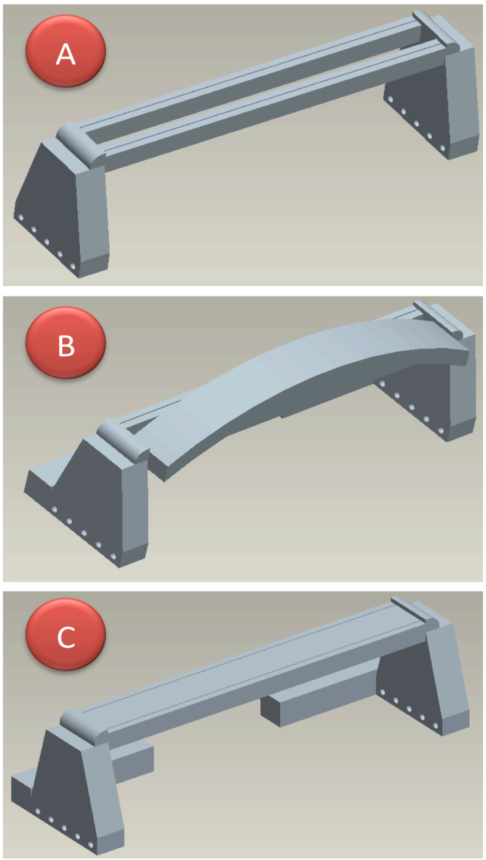


Figure 4.42: Various gantry frame designs.

Furthermore, the gantry can be integrated as a module to accommodate a wide range of standard and off-the-shelf components in order to perform any required machining process. Figure 4.43 shows a possible configuration to perform several processes (lathe, milling, drilling) by adding components such as high precision linear stages, motors, tool heads, and material holding fixtures.

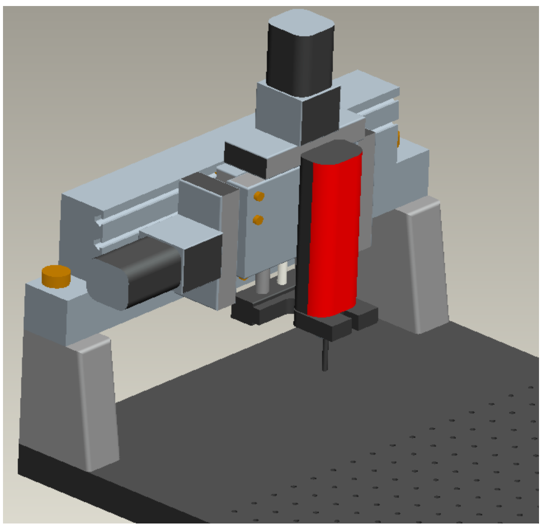


Figure 4.43: A configuration for multi machining process.

In addition to the re-configurability of the structure, using a modular control system will allow an extra level of flexibility; this level can be represented in controlling several aspects of each machining process including the performance of machining tools (speed, size, accuracy etc.). Selecting any suitable configuration of software and hardware modules for each process is one of the advantages of having a modular control system.

4.4.5.10 Production Level

Having up to seven processing modules with a small footprint cell offers the ability to cope with some of the most recent manufacturing schemes such as Lean Manufacturing, Agile Manufacturing and Just-in-Time (JIT) Manufacturing as will described in a later stage. This can be achieved by focusing on the fulfilment of fundamental principles of manufacturing including increasing productivity, decreasing cycle time, increasing utilisation and reducing inventory.

The design of the cell allows switching between some of the well-know manufacturing systems categories including Dedicated Manufacturing System (DMS), Flexible Manufacturing System (FMS) and Reconfigurable Manufacturing System (RMS). This can be attained by either using all processing modules in the cell to machine one product (work piece) or using each processing module to machine a single work piece.

4.4.5.11 Concept Assessment and Performance Analysis

This part will highlight the advantages of this novel concept over each one of the previous designs. In order to achieve this, similar assessments will first be performed by developing a Mesh of the design geometry; then observing fundamental natural frequencies and deformations. Performing a similar assessment process is critical in order to maintain comparable evaluation criteria, which will improve the validity of the concept selection process to setup the required data for further design optimisation processes as will be shown in the following sections.

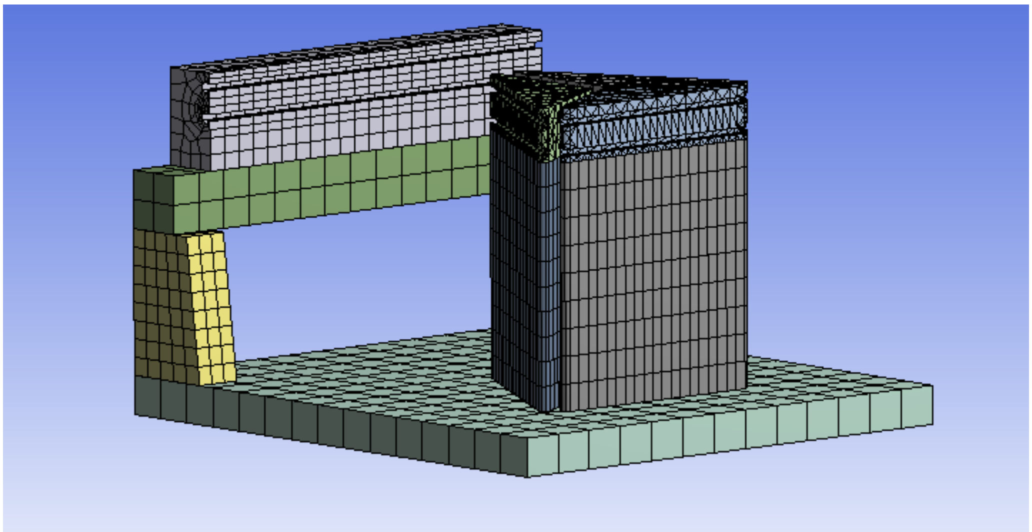


Figure 4.44: Developed Mesh of the system.

The above figure (4.44) shows a three-dimensional geometry Mesh of the fixed structure with no mechanical components attached. The reaction of this structure to any applied force will define the performance of the entire system, and will be used in analysing the stiffness and stability of the system as more details of assigned material and mechanical components will be added to the design in a later stage.

Each module and component of the structure generates a number of fundamental natural frequencies when a force is applied. Therefore, at this stage, it is important to observe the natural frequencies of the entire structure as an assembled system. Then, each part will be assessed individually to compare the performance of the part as a stand-alone unit and as a link within a chain of physical structures.

Fig. 4.45 shows five fundamental natural frequencies generated when granite and aluminium components are assembled as a structure. On the other hand, static and dynamic deformation tests illustrate a vast improvement in design stiffness. When applying 500N on the base of the structure vertically, static deflection generated only 0.4741 um, while the dynamic deformation of the structure made a displacement of 1.2 um when 50N applied.

By developing several novel concepts, assessing each concept and gathering all the required data, the following part provides a comprehensive comparison between the five concepts. This comparison aims at emphasizing the development of the final novel concept starting from pre-determined design objectives, then developing several conceptual designs, before ending up with a detailed design that is ready to be developed into a prototype.

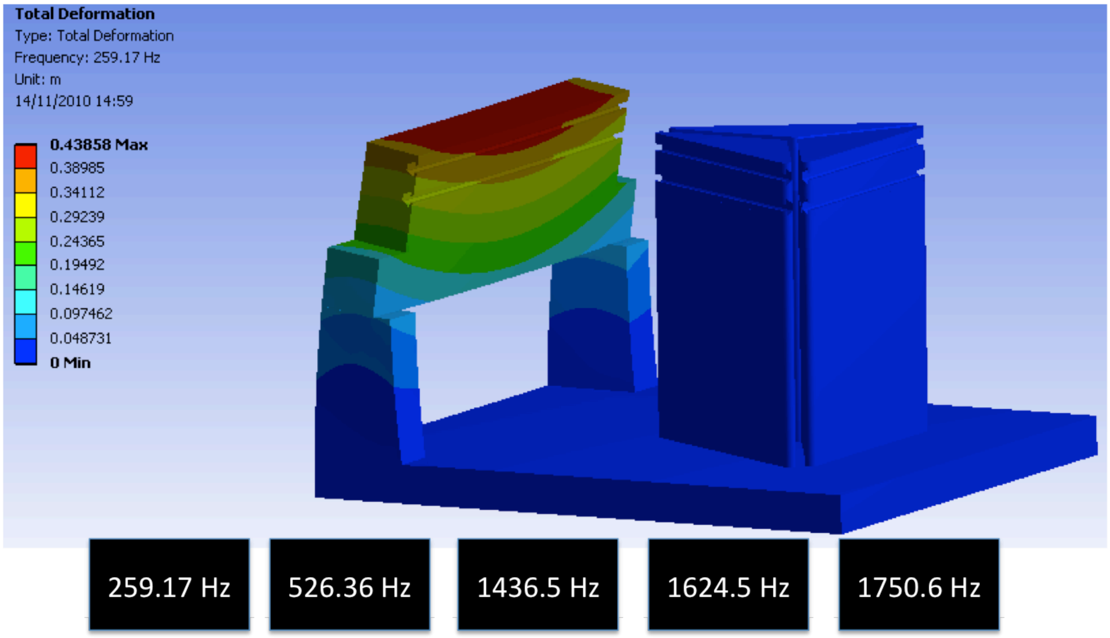


Figure. 4.45: Five Natural Frequencies of the gantry structure.

4.5 Design Iterations Assessment and Comparison

In this section, the comparison process between the five concepts focuses on the development of the novel concept based on delivering the required design criteria and performance. Therefore, the aim of this process is to identify the improvements when moving from one concept to the next. This means providing an analytical assessment of all concepts based on the performance of the structure including its stiffness. Ideally, this approach will show improvements in performance since each concept is developed based on solving performance issues and limitations from previous concepts.

To start this process, comparison and assessment criteria must be defined along with the order of developing the five concepts. Since this assessment will be based on measuring the stiffness and stability of the structure, four main stiffness aspects will be compared in all five concepts. These aspects are: static deformation, dynamic deformation, static stiffness, and dynamic stiffness.

To deliver the required machining performance, a machine tool must be statically and dynamically rigid. Its static stiffness determines its ability to produce dimensionally accurate parts while its dynamic stiffness affects the quality of the component's surface finish and the maximum metal removal rates that can be achieved (Myers, 2005). Therefore, the process of modifying geometries, material selection and assembly techniques are considered as a foundation for providing adequate structural support in order to develop a machine that is sufficiently rigid and capable of performing effeciently.

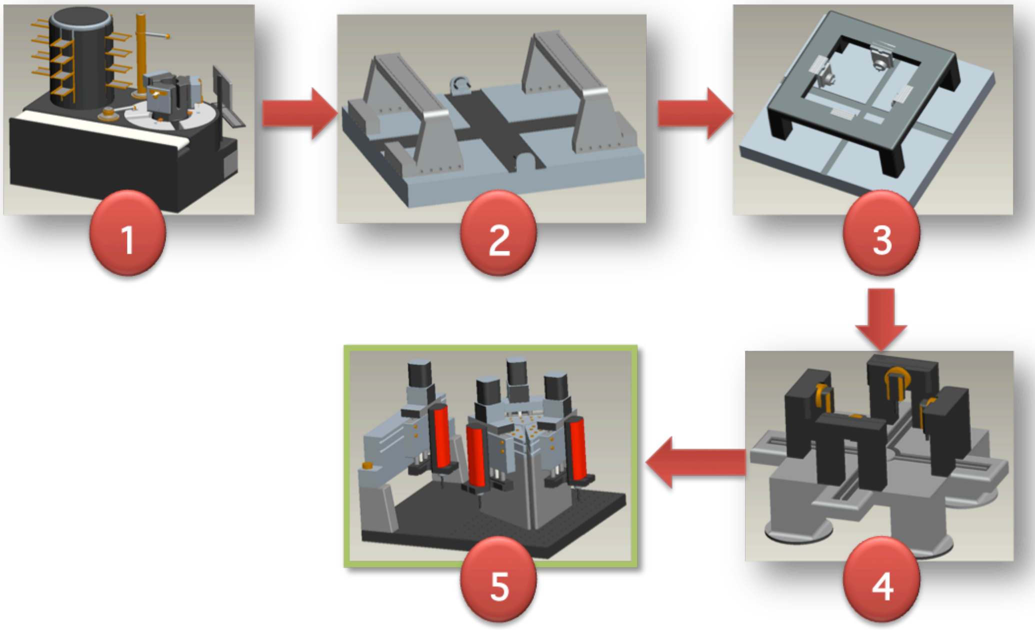


Figure 4.46: Development of conceptual designs in five stages.

Fig. 4.46 shows the previously analysed concepts as a sequence of conceptual designs that have been developed based on improving each design from one stage to the next.

By comparing the static deformation of the concepts, when equal force is applied (500N), fig. 4.47 shows a significant improvement as the process of modifying the concept develops. Starting with the first concept, which generated a significantly high deformation in the static mode with 34.62 um, this value improved during the following four design modification processes to reach a value of less than half a micro metre (0.474 um). These values justify several geometrical changes and material selection of each module within the system as described earlier in this section.

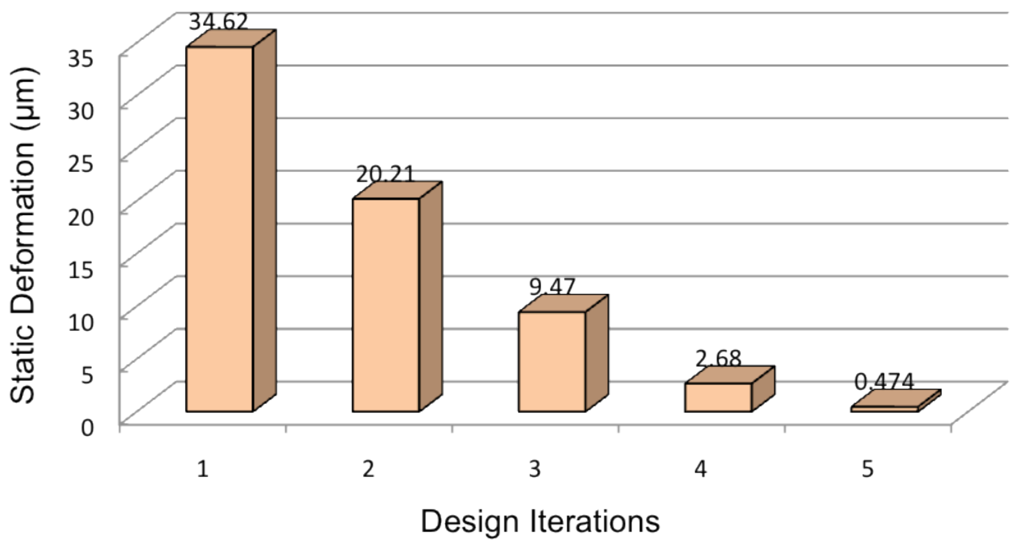


Figure 4.47: Static deformation of five design iterations.

Furthermore, measuring the dynamic deformation of each concept was a standard procedure during the design assessment. Comparing this aspect between the five concepts resulted in confirming the design optimisation process when moving from one concept to the next.

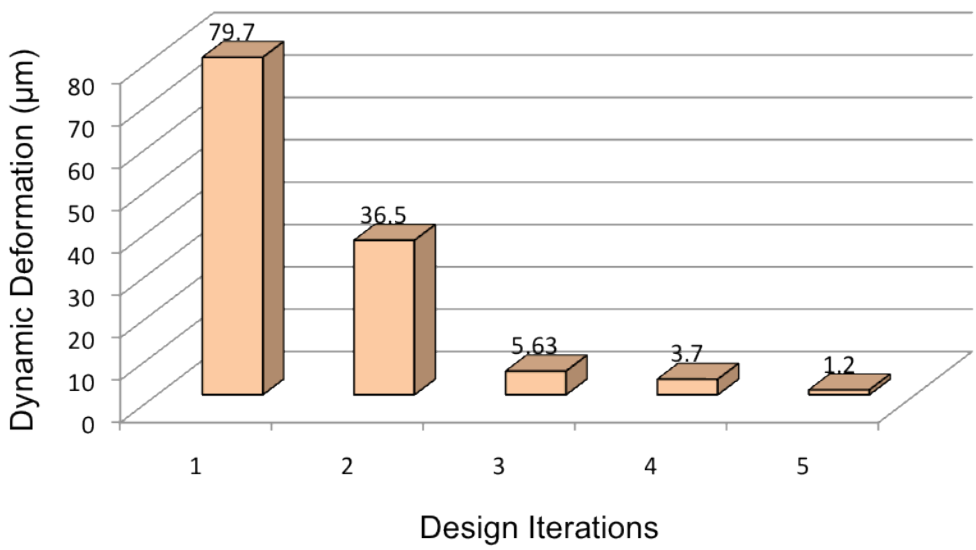


Figure 4.48: Dynamic deformation of five design iterations.

As shown in fig. 4.48, the dynamic deformation has been significantly minimised throughout the development process of a novel design, especially during the design of the third concept, which achieved a reduction from 79.7 um to 5.63 um. Moreover, these values reduced further to maintain a figure as low as 1.2 um.

Following the above steps, the concept's static and dynamic stiffness can be calculated at this stage. The importance of considering these values can be substantiated when applying a dynamic force, which is a force that changes in magnitude or direction with time. A dynamic input force will cause dynamic output motion. Because of this dynamic motion, both the stiffness due to damping and the mass stiffness effects come into consideration. Moreover, when designing a mechanical system based on delivering a high level of machining accuracy, taking stiffness values into consideration can be valuable since they represent the relationship between machine parameters and measured vibration response. Also, it can provide valuable information on changes in machine parameters and can be used to estimate the dynamic forces acting in a machine.

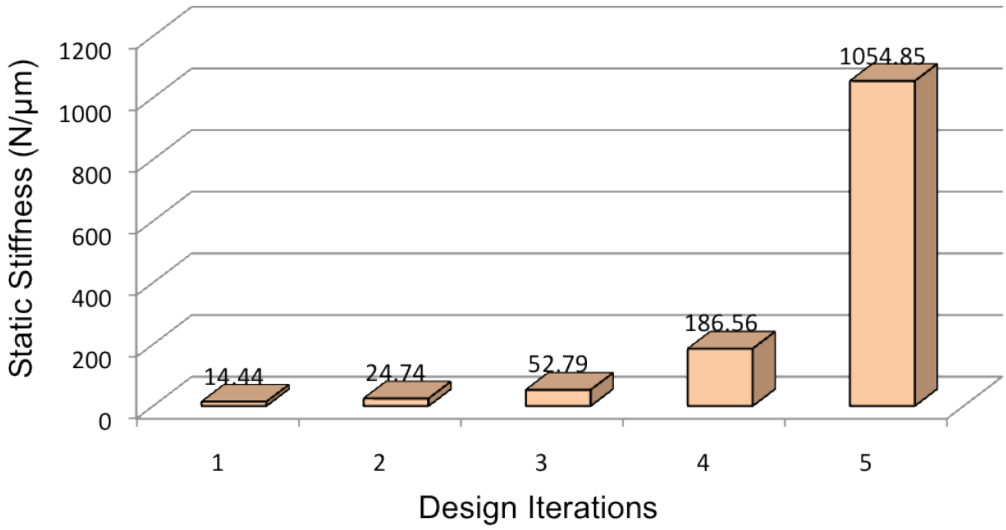


Figure 4.49: Static stiffness of five design iterations.

Comparing the static stiffness of all concepts as in fig. 4.49 shows a massive improvement regarding the stiffness of the final design compared to the previous four concepts. This can be certified by the selection of a better granite composition for the base of the structure and by the fastening method that requires less metal parts such as bolts and screws to connect between the granite module-structures within the system. Follow this, evaluating the dynamic stiffness can be achieved by using the following formula:

$K = F/\delta$
K - dynamic stiffness
F - dynamic force (N)
δ- dynamic deformation (μm)

(4.1)

The following figure (4.50) represents the progress of increasing the overall dynamic stiffness of the novel concept, starting with a first inadequate concept before eventually reaching a satisfying level of machine design with a high level of dynamic stiffness in the final stage of concept design.

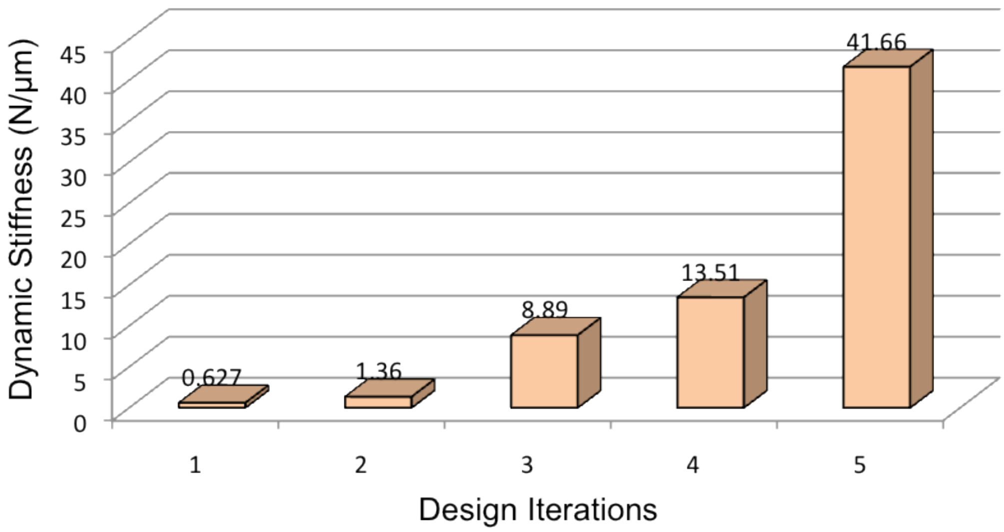


Figure 4.50: Dynamic stiffness comparison between five design iterations.

4.6 Summary

In this section, a novel design for a Re-configurable Micro-machining cell was developed based on fulfilling specific design aims and objectives. At an earlier stage, several designs were considered to build a physical model. The first design provided a performance analysis of a full micro-factory where processing modules were designed and arranged to create a hexagonal-shape structure; other supporting systems are included as well. A second design is then introduced based on assessing the performance of processing modules as these modules represent the main focus of any

Micro-manufacturing system. In this design, gantry structure was suggested for processing modules, after considering the previously mentioned advantages of this structure and examining its implementation in this research. Following this, a third and fourth design iteration have been introduced aimed at investigating several gantry structures and base designs. Finally, the fifth design was based on studying the previous four design iterations and putting together module designs and layouts that have the potential of satisfying design objectives and delivering the required performance. The fifth design iteration introduces both gantry and hexagonal module structures in order to deliver the required design reconfigurability, using different types of material and fastening techniques.

Furthermore, a performance analysis was included at this stage in order to justify the progress of the design process in this research. This analysis focused on comparing the five designs based on static deformation, dynamic deformation, static stiffness and dynamic stiffness. The results of this analysis show a substantial improvement between the first and fifth design iterations.

The selected design will be used to build a physical model (Prototype) in order to physically evaluate, validate and optimise the concept. The next section will focus on the building process of the prototype, providing a detailed description of all parts and components within the system.

Chapter 5:

Developing the Prototype

Chapter 5 - Developing the prototype

5.1 Introduction

After verifying the conceptual design in order to make sure that the proposed design is capable of performing any required machining process, a prototype is ready to be built and tested to evaluate the physical performance of the system as stated earlier in the design methodology (fig 5.1).

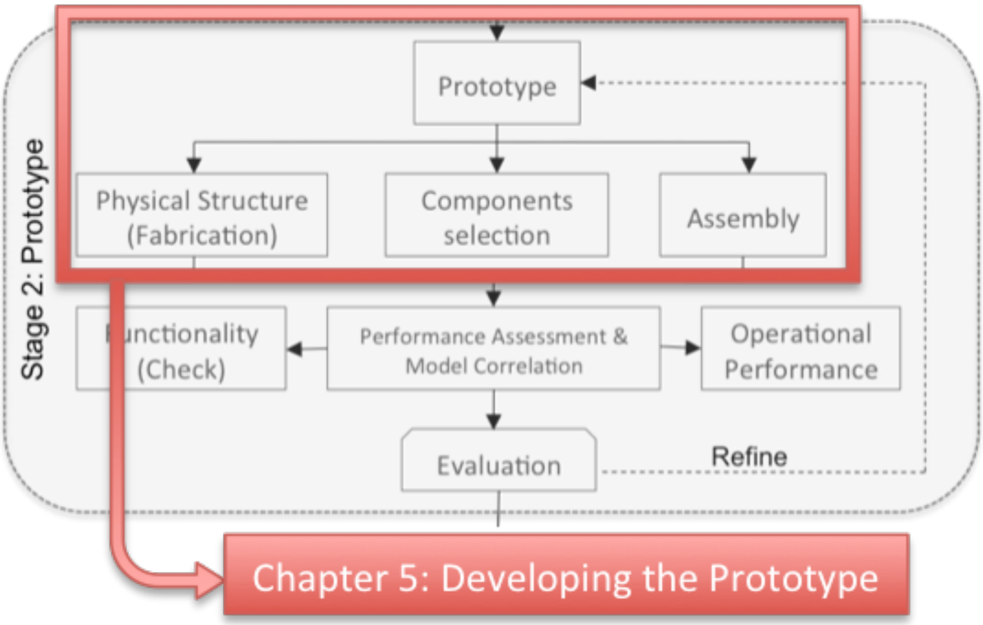


Figure 5.1: Prototype development stage.

This includes fabricating custom-made parts using different materials and acquiring off the shelf mechanical components. Following this, a detailed assembly process will take place by putting together all components within a small footprint representing the prototype of the re-configurable micro-manufacturing cell.

Several considerations have been highlighted before building a prototype of the proposed concept, including time scale and cost. These two factors have influenced the material selection, optimisation and performance assessment processes of this project. Therefore, the main requirements have been set at this stage as shown in (fig. 5.2).

Material and Components Selection Criteria

Material	Mechanical Components	Control Unit
•Robust •Durable •Corrosion Resistance	•High precision •Off-the-Shelf •Modular •Availability •Affordability	*Standard UI •Modular •Upgradable

Figure 5.2: Prototype's material and components selection criteria.

5.2 Material selection

In this project, the main structure is built using two types of material. These are Granite and Aluminium. The reason for selecting these materials is to provide the prototype with required support to deliver a satisfying performance.

However, due to the excessive thermal expansion co efficiency of aluminium, and the limited strength of the joints, applications are generally limited to low force operations such as very light machining or assembly. In rapid machine design, (Bamberg, 2000) suggested that fabrication is the preferred technique because of the following key advantages:

• Low fixed costs make it highly suitable for low to medium production volume.

• Fabrication can easily be done in-house, making the need for outsourcing obsolete.

• Use of highly standardized materials ensures high availability and competitive prices.

• Fabrication equipment is fairly inexpensive.

• Minimum tooling costs. Fabricated structures only need some form of casting which is universally applicable. No expensive moulds are required.

• Minimum lead-time as no moulds are required, this advantage shortens design to-manufacture time.

• Great scalability means no re-tooling is required when scaling the design to change available work volume.

• High design flexibility indicates that future design changes are not impaired by existing tooling, making the modification process inexpensive and easy to implement.

• Modular components can initially be fabricated separately and then joined whenever it is convenient.

Base, Hexagonal module and Gantry supports were built using artificial granite. Granite was selected due to its superior material characteristics including, high damping, lower noise levels, resistance to most known coolants, oils and chemicals and high static dynamic stiffness, giving improved tool life and surface finish, fewer costly down-times and lower tooling outlay (fig. 5.3).

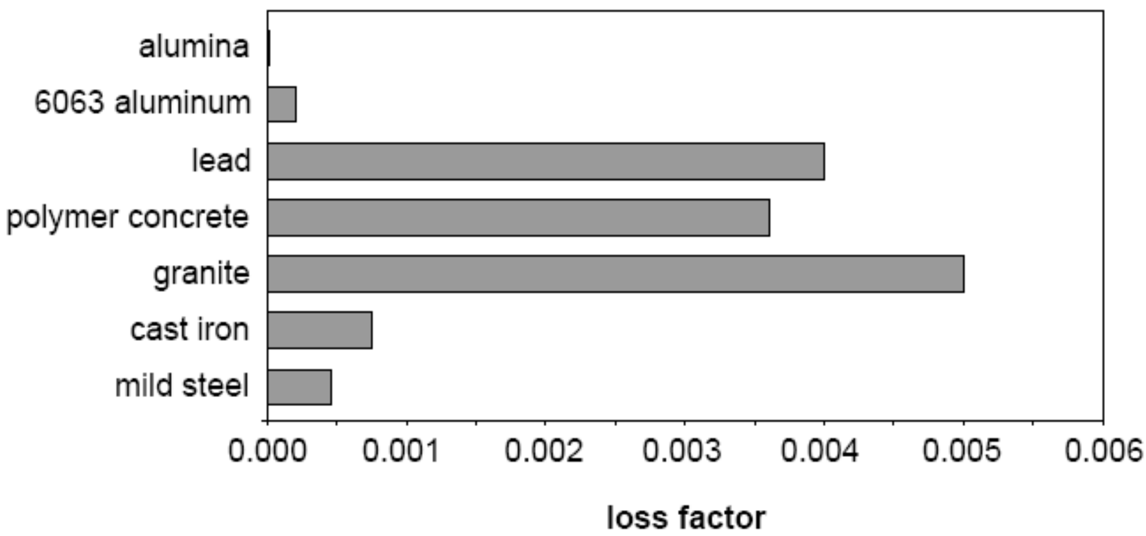


Figure 5.3: Comparison between granite and several prototyping materials for RMC.

The granite used in this project has certain specifications as shown in table 5-1. The aluminium used in this project is HE30/6082**.** This type of Aluminium Alloy (6082) has a medium strength and is extremely resistant to corrosion. It has a number of useful properties, including high strength, in contrast to other, older aluminium alloys. It is often used to build structures because of its high mechanical strength.

It is also often used for machining for the same reasons. It contains a large amount of manganese, which contributes to its strength. Mechanically, it has a proof stress of 60 MPa. Its tensile strength is 130 MPa. It has shear strength of 85 MPa. It has an elongation rate of 27 percent. It has a hardness of 35 (kgf/mm^2) as measured on the Vickers hardness rate.

Table 5-1. Specifications of granite used in building the structure of the RMC.

Density	2300-2400 kg/m3
Compressive Strength	90-110 N/mm2
Tensile Strength	18-21 N/mm2
Bending Strength	19-21 N/mm2
Modulus of Elasticity	37-45 kN/mm2
Thermal Conductivity	1.56-1.63 W/m °C
Thermal Expansion	11-13 x10-6/0
Poisson's Ratio	0.25

5.3 Main components

There are two main structures in this project which creates the RMC, physical (fixed) structure and Mechanical (Dynamic) components.

5.3.1 Physical structure

The three main parts include a base and two reconfigurable modules representing the physical structure of the micro-manufacturing machine cell. The fastening process in the system is performed using conventional festinating components to ensure compatibility with any off the shelf mechanical or electrical components.

5.3.1.1 Granite Base

This base is a single cast artificial granite part covering the entire footprint of the cell. It is designed to provide the system with a level of flexibility by dedicating 60% of its surface area to an assembly area for other static and dynamic components. This area is covered with 187 identical holes that allow fixing other components in a variety of configurations and arrangements. Also, it has dedicated fixation points to attach a static gantry structure. Fixing two identical granite gantry supports to the base is done using two standard M6 bolts for an easy assembly process (fig. 5.4).

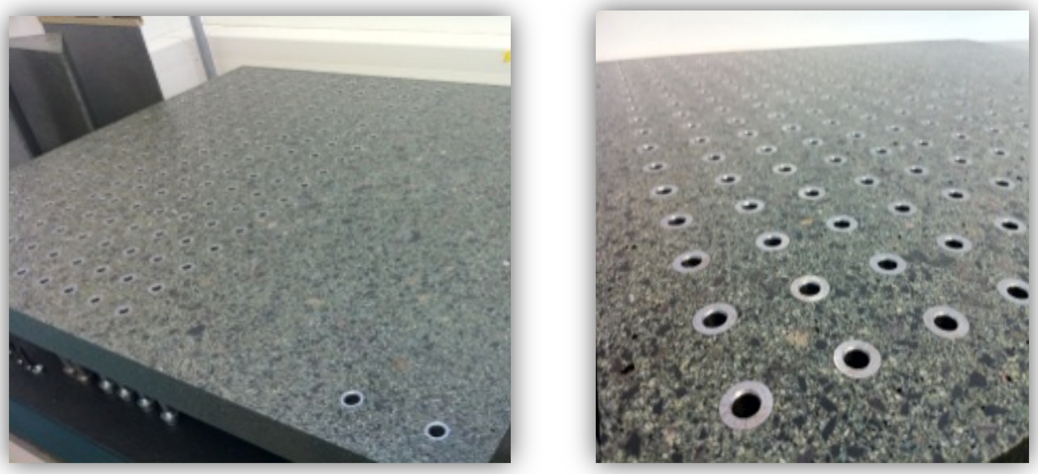


Figure 5.4: Overview of the granite base design.

5.3.1.2 Hexagonal Module

As described in chapter 4, this module will be used as a base to hold a wide range of mechanical components that will perform the machining processes. Several design optimisation steps have been considered before building the prototype which include modifying the geometry of the module. During the first attempt to design a processing module that satisfies the machining requirements of this project, a regular Hexagonal shape was developed. The aim of choosing such a design is to have three faces of the shape to hold three machine tools and perform as individual machining zones, while the other three surfaces separate them as in figure 5.5.

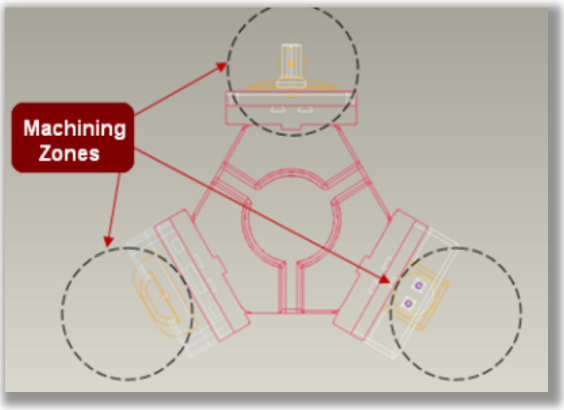


Figure 5.5: Original design of the processing module.

It has however, been noticed that the layout of this module can be optimised in order to achieve better utilisation and machining quality. Since the size of the surface area is directly related to the size of the work-envelope, it is important to optimise the geometry of the machining zones in the hexagonal module in order to maintain the required work-envelope.

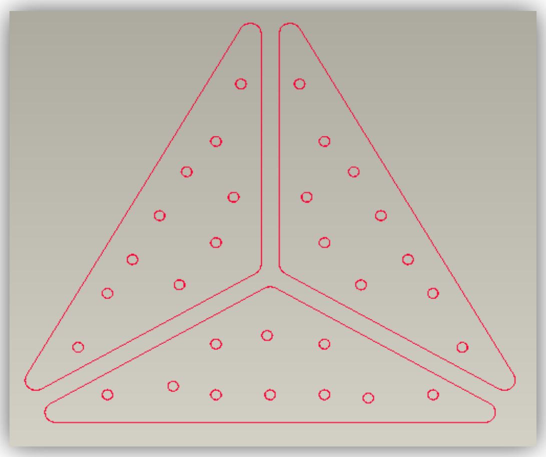


Figure 5.6: Layout and dimensions of the Hexagonal Module.

The current machining zone surface is considered small compared to the mechanical components that will be attached to it. Therefore, the size (surface area) of the three machining zones was increased from (60 mm width and 140 mm height) to (240 mm width and 250 mm height) as in figures 5.6 and 5.7. Moreover, this step has been achieved while maintaining the key design feature of having the three machine zones separated and facing different directions.

The first machining module is the hexagonal part, which will be fixed to the base using fastening screws connecting the base of each one of the three parts of the modules to the top of the granite base. As mentioned earlier, the unique design of the ten fixation points presented in this module allows each individual part to be attached to the base in different orientations. This design feature will increase the re-configurability and flexibility of the system by providing various cell layouts to be used, based on the required machine processes and production strategy. Moreover, the top surface of the module will use the same technique to fix aluminium parts on the top of the hexagonal module described later in this section.

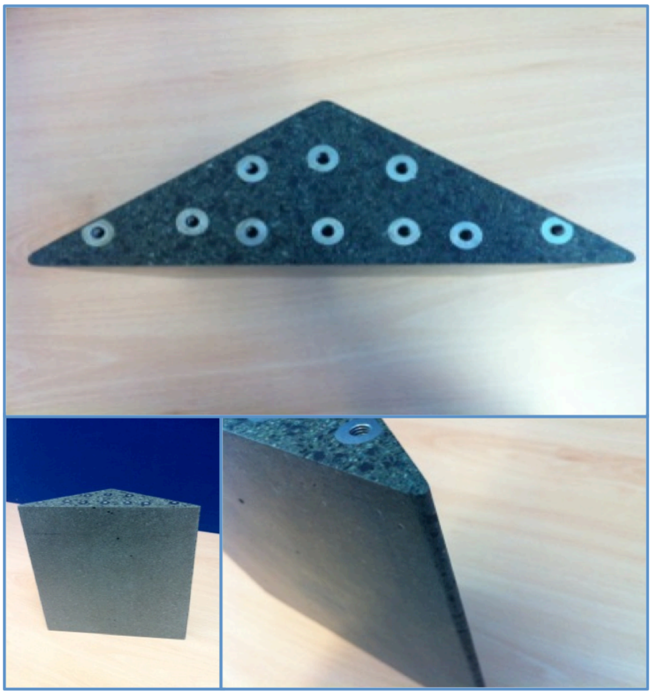


Figure 5.7: Overview of a single part of the granite Hexagonal Module.

As shown in figure 5.8, one suggested layout of the hexagonal structure is fixture to the base ready for more parts and mechanical components to be added to the cell before performing machining processes and tests.

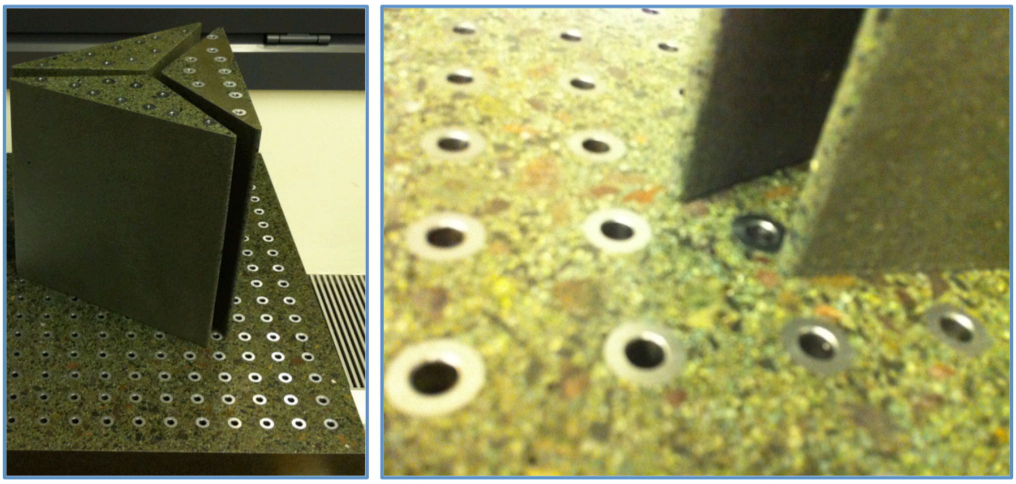


Figure 5.8: The granite Hexagonal Module assembled.

5.3.1.3 Gantry structure Support

The reason for adding these two identical parts to the cell is for use as support to the gantry structure by connecting it to the granite base in two locations. Considering the physical and mechanical properties of the granite, these two supports will provide a superior sustainability to the gantry structure, avoiding any physical deformation or thermal expansion. They will also reduce the vibration which results from performing machining processes and moving mechanical components.

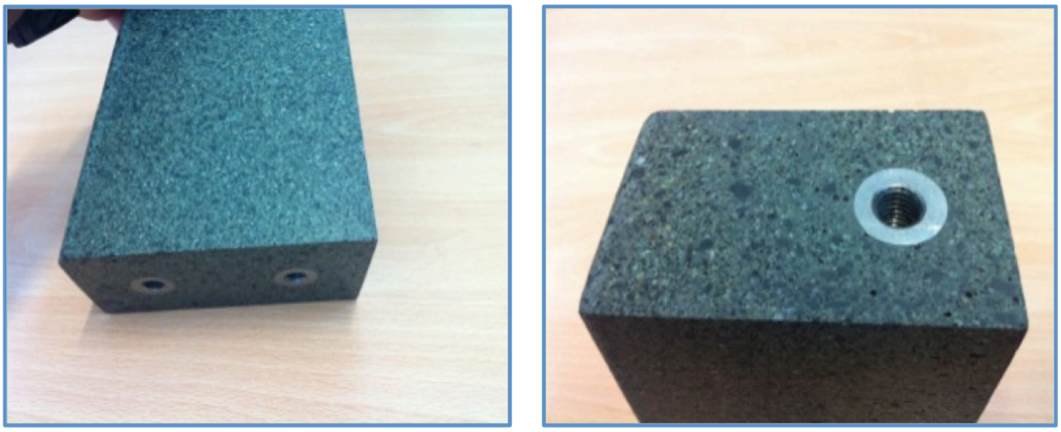


Figure 5.9: The granite supports.

The supports have been produced for this prototype using a single mould in order to achieve a faster production time and minimise production costs. As shown in figure 5.9, the base of each granite support was designed to include two insertions for M6 screws. The purpose of this feature is to connect this part to the base in two positions. Moreover, considering that the bottom surface of each support is longer than the top surface, only one insertion space was made on the top surface aimed at connecting the support with the gantry structure. Therefore, the size of screw used in this position (M8) is relatively bigger than the one used in the bottom (M6).

5.3.1.4 Aluminium Gantry structure

The purpose of including aluminium parts in the system is to connect the mechanical components to granite structures. Such an approach was considered because of the required time and cost to complete the assembly process of the cell.

In this project, two main structures are made of Aluminium 6082 which are attached directly to the previously mentioned granite modules using standard fastening tools such as bolts, nuts and washers. The two aluminium structures are represented by a single-part gantry structure and a set of three triangle units fixed on top of the hexagonal module.

The following design and production issues have been considered before machining each aluminium part in this system:

- Each part should be machined from one solid block of aluminium. This approach aims at maintaining the physical and mechanical robustness of each part by avoiding any assembly process to produce these parts.
- Since these parts will be fitted in the system in order to connect mechanical components to the solid structure, they have been designed and machined to be compatible with a wide range of industry standard and off-the-shelve components.
- High precision machining is required to produce each one of the aluminium mounts due to the precise position of the ten surface holes on the top and bottom of the parts and to ensure a good surface quality.

Figure 5.10: Overview of a single part gantry structure.

As shown in figure 5.10, the structure is made by fabricating a single piece of aluminium which is machined to have two identical channels. These channels will be fitted with standard T-nuts in order to attach high precision linear stages. Also, two M8-size holes have been machined on the sides of the structure to match the holes in the granite supports. Once the structure is mounted and fixed using M8 screws it is ready to accommodate any configuration of linear stages (fig. 5.11).

Figure 5.11: Assembled gantry structure.

5.3.1.5 Aluminium Mounting Unit

Including these units (fig. 5.12) within the system can be justified as follows:

- Considering the time-scale and the cost of building the prototype in this project, aluminium is faster and easier to machine compared to granite. Therefore, many concepts have been developed during the past few years using aluminium only as a material of choice due to its high durability and machinability.

- Using aluminium to make these parts allows modification of these parts according to any future requirements. This includes re-machining the parts or fixing new parts in order to achieve higher performance or better design utilisation.

- In case of the need to replace or change the fixation method in the future, only aluminium units can be replaced without the need to modify, replace or re-design the entire structure of the two modules. This method increases the upgradability level of the system while maintaining a low-cost approach.

Figure 5.12: Overview of aluminium mount units

Mounting each unit on top of the hexagonal module requires fastening each part in ten pre-defined positions using M6 screws. On the other hand, T-nuts are required to attach linear stages to the aluminium mount. Each T-nut will be placed in each channel and matching size bolts (M6 in this project) will be bolted through as in figure 5.13.

Figure 5.13: Assembled Hexagonal module with T-nuts.

5.3.2 Mechanical Components

Components used to perfom and control machining processes were selected and acquired in order to test and investigate the cabability of the system. Therefore, each element needs to be integrated with all other components within the system.

5.3.2.1 Fastening Tools and Components

Various fastening and assembly techniques have been used to put modules together within the system. Essentially, the requirements of these parts include standard design, high quality, reliability and modularity. Moreover, three main fastening part families have been used in this project: Bolts (screws), Nuts, and Washers.

Based on the application of each component, a variety of material, sizes and specifications were required for each part. For example, M6 Zinc socket cap screws were used to attach aluminium mounts to the hexagonal module while socket countersunk screws were needed to assemble each set of linear stages. Figure 5.14 shows a sample of parts used in the assembly of the gantry structure.

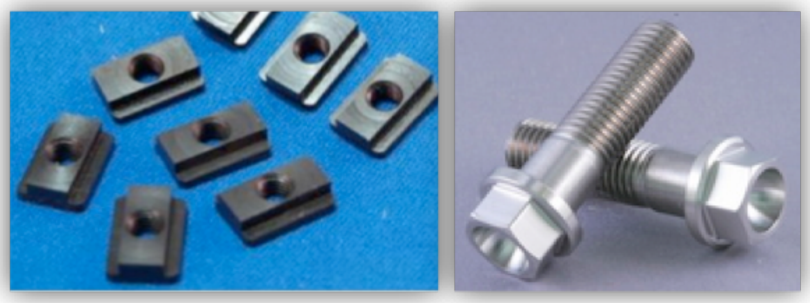


Figure 5.14: Fastening parts, screws and T-nuts.

5.3.2.2 Mechanical Components and Control System

Once the main two structures are fixed to the base, mechanical parts can be added in order to perform machining processes. Due to the high flexibility of each part in the system, a wide range of combinations can be employed and reconfigured based on the machining and production requirements. For example, any two precision linear stages can be put together to provide different degrees of freedom such as (x,y) (y,z) or (z). This process starts with the assembly of the linear stages configuration (fig. 5.15).

Depending on the required machining process, degrees-of-freedom and work piece specifications, two linear stages will be attached together providing the needed working axes. Each stage includes a stepper motor that actuates the metal plate of each stage and provides a high precision movement.

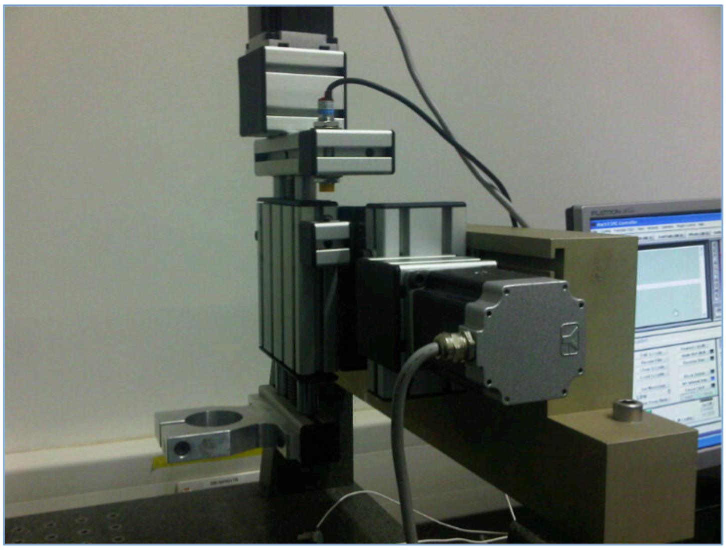


Figure 5.15: Assembled Z,Y configuration.

Afterward, a high speed milling motor is attached to the configuration. A universal motor is used in this project (Kress 1050 FME 240V Milling Motor) and attached using a standard aluminium collet. Ideally, four motors can be attached to the system to perform machining processes simultaniously; three fixed to the sides of the hexagonal module, and a single motor for the gantry structure. Then, all these components will be connected to a control unit in order to set up and manage each aspect of the machining process using a PC-based control software (fig. 5.16).

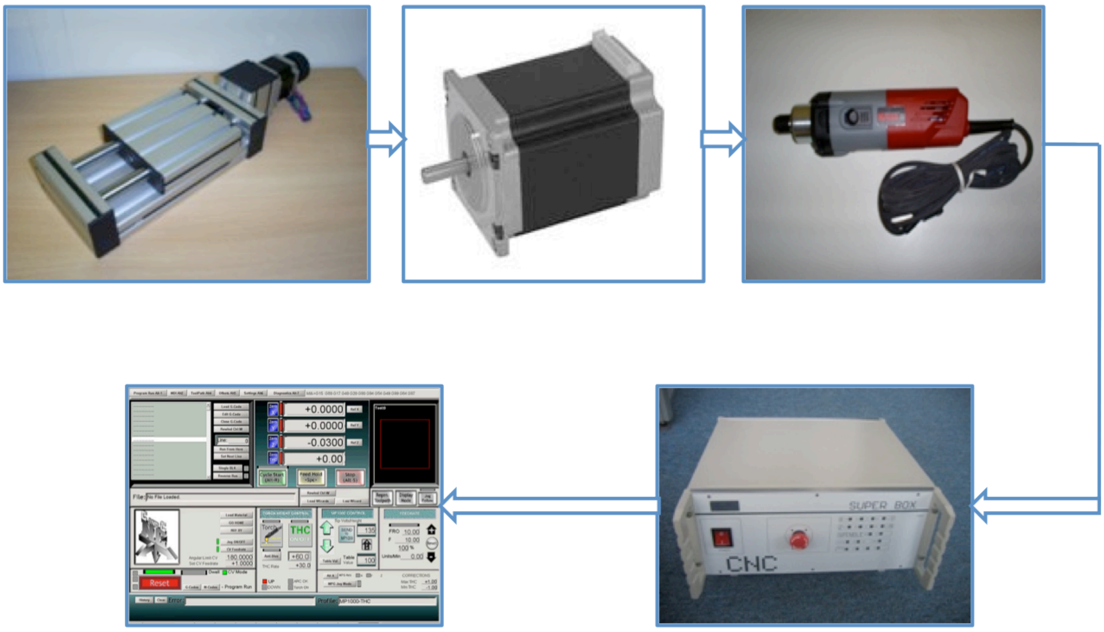


Figure 5.16: Component assembly and control system configuration.

5.4 Summary

This chapter has provided a step-by-step description of the development of the prototype, starting with a substantiated selection process of material and mechanical componenets, followed by the assembly process of these components. At this stage, the Re-configurable micro-machining cell is assembled, set-up and ready to be tested. In the next section, a performance assessment process will be performend in order to investigate the stability, performance and productivity of the prototype.

Chapter 6:

Performance Assessment and Analysis

Chapter 6 - Performance Assessments and Analysis

6.1 Introduction

In this chapter, a performance assessment of the conceptual design (model), and physical structure (prototype) will be performed following the iterative design approach in this project (fig. 6.1).

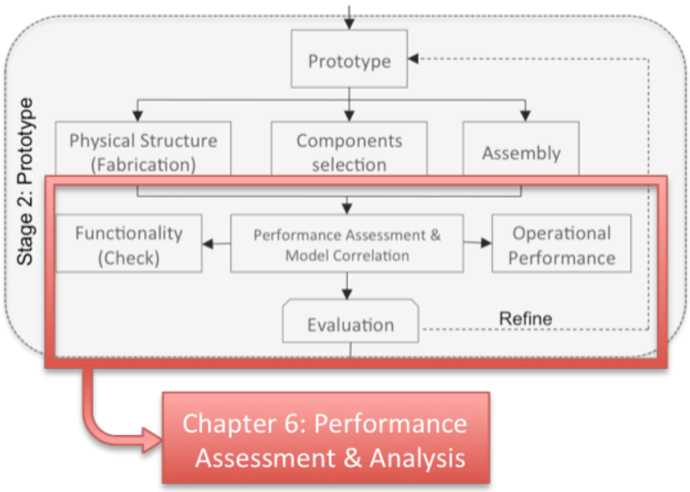


Figure 6.1: Design and performance experiments loop.

This approach aims to provide a full understanding of the RMC's performance, which leads to identifying limitations and weaknesses before starting a design optimisation procedure. The assessment process includes reviewing the set-up of each experiment, developing static and dynamic models, optimising these models and testing the performance of the prototype.

6.1.1 Overview

Validating a novel architecture is a crucial step in the design process. Therefore, identifying the performance level of the Re-configurable micro-manufacturing cell must be considered before, during and after building the prototype. This method is performed using finite elements analysis (FEA) and simulation software. This process involves a static analysis in order to study the reaction of the granite base with all processing modules attached to it. This requires attaching each module to the base in order to calculate the loads and displacement. This must also be based on the selected geometries and used material of each module. A mesh will be produced in order to evaluate the reaction of each part to any applied loads including gravity. This is a key step to estimate the stability and precision of each machining process. Therefore, the damping level can be increased in order to have more precise processes. This approach gives an overview of the cell's reaction to the load of each component attached to the granite base, gantry supports and the hexagonal module. Calculating the maximum dynamic displacement during each mode will then be considered by developing a dynamic model in order to calculate the deformation that may occur during performing any machining process.

6.1.2 Assessment Aim and Objectives

In this project, the design assessment process aims at validating the design of the RMC by testing its performance under different operating, machining, and production conditions.

In order to achieve this, several assessment objectives need to be satisfied, starting with developing a compelling correlation between conceptual design, which is represented by the Finite Element Model (FEA), and the prototype (physical model). This is a significant step in developing and optimising the current design without the need to build another prototype. This is based on a trial-and-error method. Having a high level of correlation between the two models indicates a high correspondence when any future optimisation is required.

The assessment approach which has been used to investigate the precision of the re-configurable micro-manufacturing cell is based on measuring the overall displacement occurred in various conditions (pre-machining and during machining). This approach is based on discovering a correlation between the static structure of the cell and FEA model. In order to accomplish this, the natural frequencies of each model need to be developed and observed. For this, a FEA model will be developed using ANSYS FEA modelling software. Natural frequencies of the prototype can be observed by starting hammer test.

Based on the output of each test, a correlation will be made between the two models and an optimisation step will be considered and performed in order to increase the level of similarity between them. Mechanical components will then be attached to the prototype and included in the conceptual model in order to perform another test. The second test aims to measure the acceleration of each module in the system using sensitive accelerometers. The measured acceleration can be converted to displacement using mathematical equations at a further stage.

Furthermore, in order to come up with all required data to carry out these calculations, a sequence of experiments will be conducted as in (fig. 6.2). Each experiment consists of a number of tests.

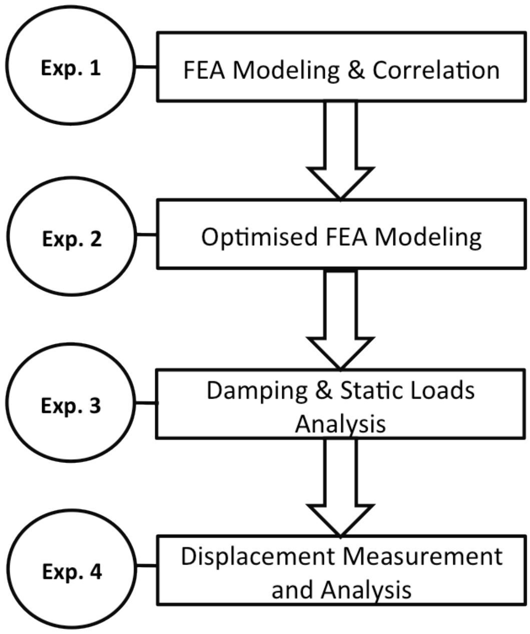


Figure 6.2: Four design and performance experiments.

6.2 Prototype Experiments and Analysis

Before starting any of the previously mentioned experiments, a set-up of measurement hardware and software must be appointed. Fig. 6.3 represents a default set-up of equipment used in this project where each experiment requires a modified set-up.

Starting with measurement sensors, two types of sensors were used in this project in order to perform physical structure analysis. The first type is a non-contact displacement sensor (1), which is usually used to measure displacement with high accuracy, providing reading in micro and nano metre scale. In this project, the sensor is used to measure the displacement of several parts of the structure including main structure and mechanical components. This sensor has two channels (In/Out), the first channel (Out) is connected to a gauge module (4), which is used to calibrate and set-up the sensor before taking any readings.

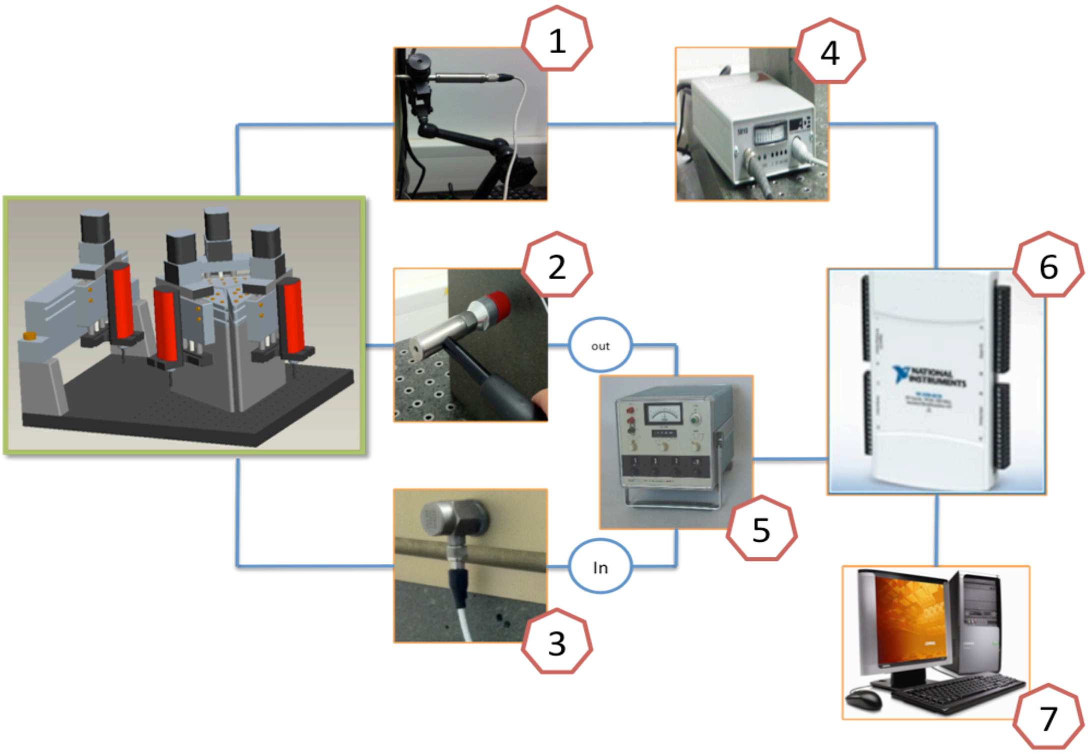


Figure 6.3: Experiments set-up and equipments.

While the other channel is connected to a an accelerometer sensor (3), this sensor is attached to the structure using a special type of wax in order to measure the reaction of the structure once a force is applied or excitation occurs. This force can be applied by a testing hammer (2), which is applied by making physical impact in order to generate a certain amount of vibration within a specific area of the structure. All accelerometers and sensors are connected to a Data Acquisition Card (6) via a voltmeter (5) and the gauge modular. The (DAC) receives several readings simultaneously, depending on the card's capacity, before sending them to a PC-based control system (7). The user interface of the control system reads and analyses the data from the card and creates a database for each experiment.

6.2.1 Experiment 1: FEA Modelling and Correlation.

This experiment aims to develop a correlation between the 3D FEA model (Concept) and the physical model (Prototype). This can be achieved by following a 3-Step analysis process. First step, the model will analyse the basic machine structure consisting of fixed parts only, without including any moving or mechanical components. This structure includes a 3D CAD model generating assigned material and assembly. Additionally, Mesh is produced based on the provided information and followed by running a simulation in order to observe the Natural Frequencies of the model.

Granite	(x1) Granite Base	(x3) Hexagonal Structure	(x2) Gantry Support
Aluminium	(x3) Mounts	(x1) Gantry	

This step involves assembling a prototype in order to match the conceptual model in the simulation. Next, an experiment using input (Hammer) and output (Accelerometer) devices will be analysed in order to compare the outcomes between steps 1 and 2.

In the second step, only one accelerometer is connected to each of the main parts of the machine structure, aimed at applying a certain amount of force using the hammer to operate the accelerometer to read the resulted frequency. The first position to measure the natural frequency of the structure is the aluminium gantry as this represents the weakest point in the system. Following this, the granite supports of the gantry structure must be tested as well since they are made of different material. Finally, the accelerometer will be attached to the hexagonal structure to perform the same test (fig. 6.4).

Figure 6.4: Positions of accelerometers and excitation points.

The first step produced a model that shows an accelerated structure in several phases. These phases represent the Natural frequencies of the structure. Based on the reaction of the structure, a range of fundamental natural frequencies have been observed. These natural frequencies were generated at the weakest point of the structure (Aluminium Gantry) with a value of 259.17 Hz. In order to confirm the above result, the physical test needed to generate the same type of reaction from the same part.

FEA Model	Hammer Testing
259.17 Hz	250.1 Hz

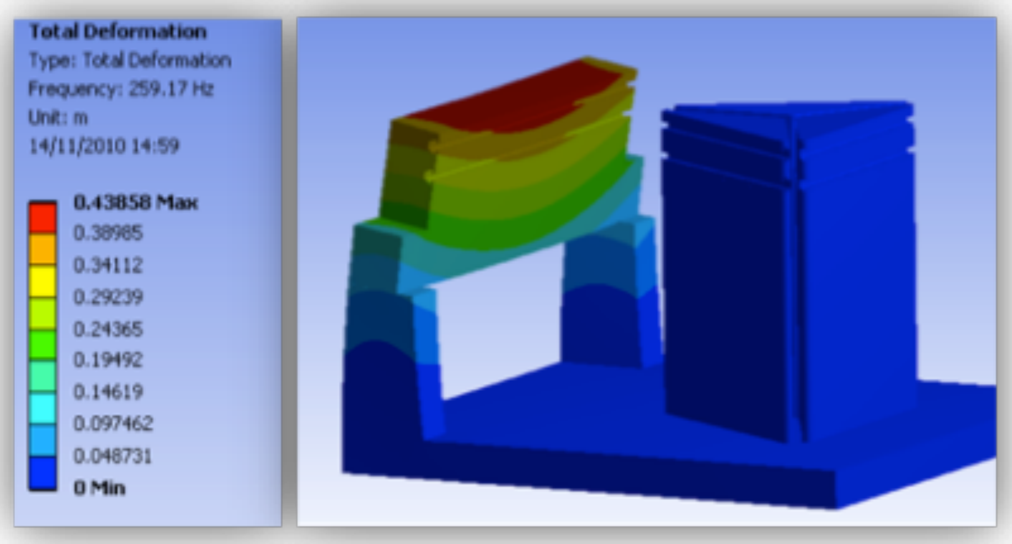


Figure 6.5: Gantry structure during the fundamental natural frequency mode.

Therefore, an accelerometer was attached to the rear side of the aluminium gantry in order to measure the output signal of this part once the hammer hits it. The resulted fundamental natural frequency of this part was 250.1 Hz.

The difference between the two tests (9 Hz) can be justified as follows: FEA model assumed that the aluminium gantry and the granite supports are attached surface-to-surface, while in fact the two parts were bolted together. Based on the above observations, the model needs to be optimised in order to reduce the difference between the model and prototype. Meanwhile, the Hammer test produced very consistent results. The generated frequencies were almost the same every time a part was tested in the system. In addition, the Hammer testing provided a high level of accuracy and repeatability. Each time, 10,000 signals are generated (readings) with ±0.0001 (mm) accuracy, providing more readings and data for further analysis in a later stage.

6.2.2 Experiment 2: Optimised FEA Model and Correlation Process

In order to come up with a better and more reliable FEA model, several modifications need to be considered before running simulation. To specify, this process included adding more design features in the FEA model, to result in a more realistic and accurate model. However, such a process will increase the simulation time and the usage of CPU power.

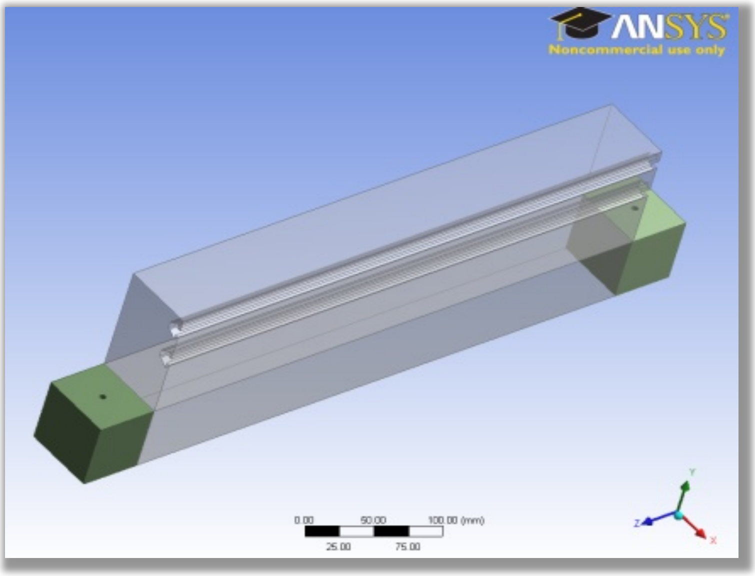


Figure 6.6: Optimised gantry structure design.

Re-drawing the gantry structure to include the two fastening holes connecting the gantry part to the granite supports (Fig. 6.6) is the first model optimisation step. Connecting the gantry to the supports was then based on facing the base of the gantry to the top surface of the granite base. This was not the most accurate fastening method when assembling the prototype. In order to solve this issue, a more detailed 3D model was produced to include all design features and fastening methods. These modifications resulted in a more realistic FEA model compared to previous models, which can be identified in the following section.

Experiment 2: Results Fundamental Natural Frequency

The first result of the above design modification process comes from generating an optimised model of the gantry structure within the fundamental natural frequency mode. This model shows better correlation to the actual natural frequency value that was measured physically using the hammer testing method. As shown in table (6-1), the correlation accuracy has improved by 2.5% due to the modification of the FEA model. The hammer test result is almost the same, which indicates a high level of consistency (fig. 6.7).

Table 6.1- Correlation accuracy of old and modified models.

	FEA Model (Hz)	**Hammer Test (Hz)**	**Accuracy (%)**
Modified Model	248.42	251	98,9
Old Model	259.17	250	96.4

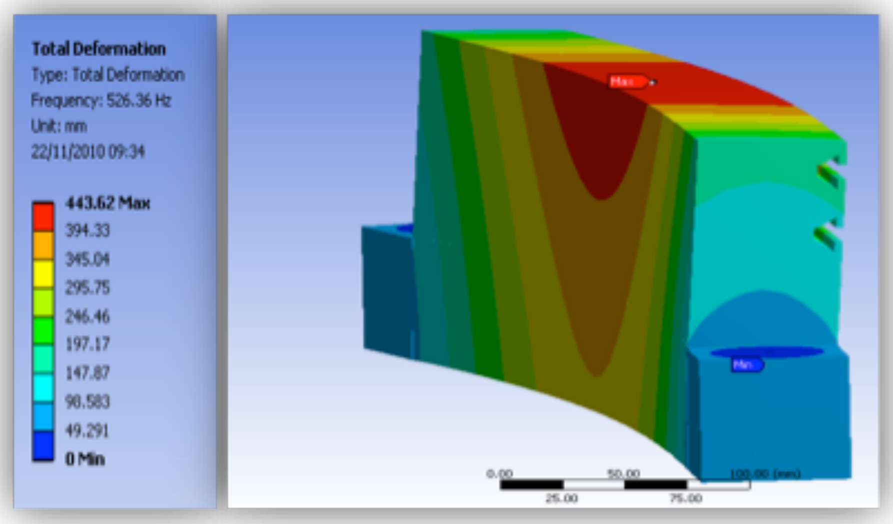


Figure 6.7-6.8: Optimised gantry structure (fundamental natural frequency mode).

Hexagonal Module: In contrast, each part of the hexagonal module achieved correlation accuracy above 98% as in (Fig. 6.9) and table 6-2.

Table 6.2 - Correlation accuracy of Optimised part from hexagonal module.

FEA Model (Hz)	**Hammer Test (Hz)**	**Accuracy (%)**	**Error (%)**
947.75	966	98,1	1,9

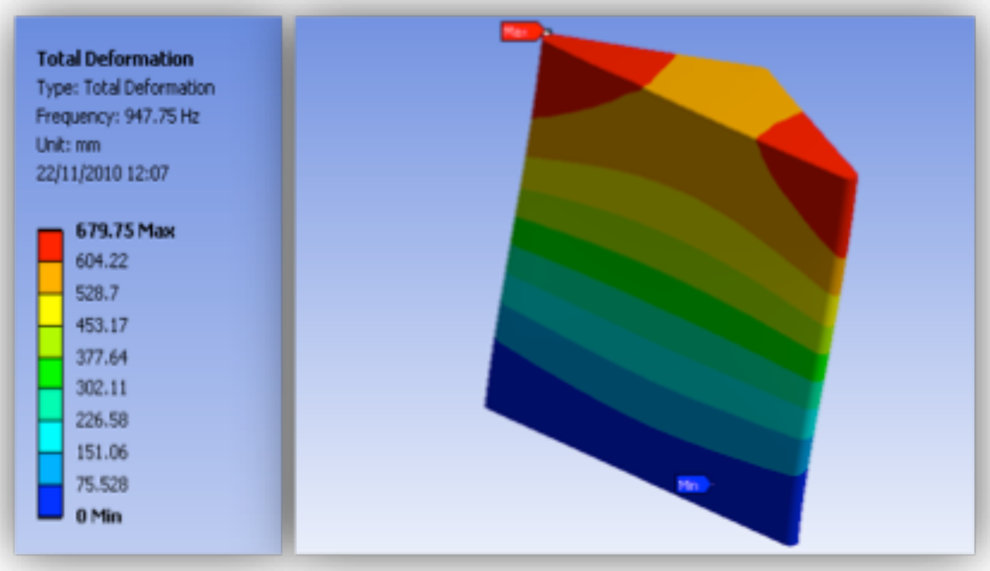


Figure 6.9: Optimised part from hexagonal module.

Granite Support: Since the two granite supports are supporting the gantry structure, both parts are involved in the fundamental natural frequency mode. The effect of this mode can be observed in figure 6.10 where the top surface of each part is facing more pressure than the bottom surface. This pressure occurs due to the load and friction caused by carrying the aluminium gantry structure.

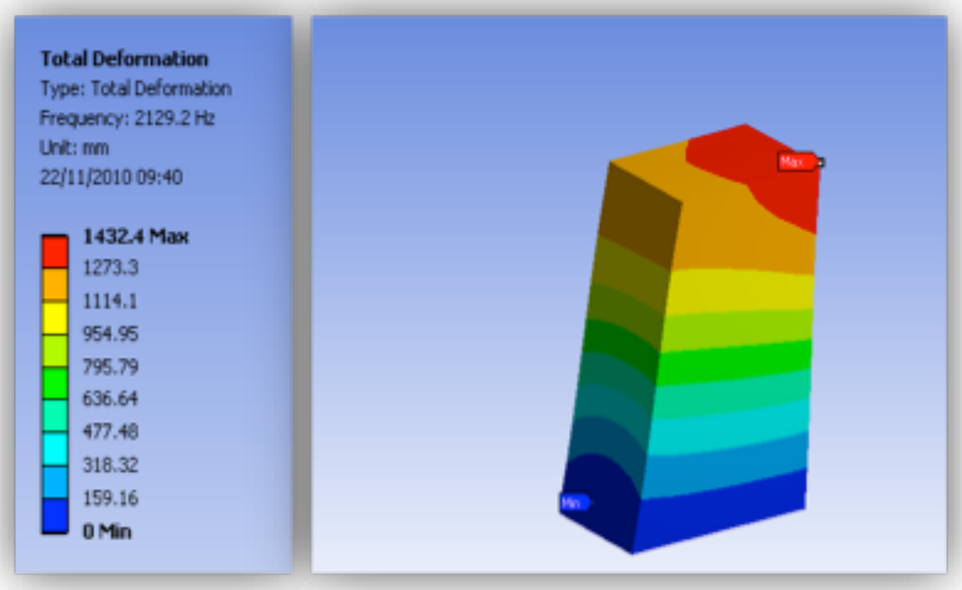


Figure 6.10: Optimised granite support.

For the same reasons, the conceptual model of this part is enhanced due to the improvement of the gantry structure's design. This design optimisation means achieving better correlation for both parts with the physical prototype.

Table 6.3 - Correlation accuracy of the optimised gantry support.

FEA Model (Hz)	Hammer Test (Hz)	Accuracy (%)	Error (%)
2129.2	2101	98,6	1,4

Granite Base: The correlation between both models for the modified design of the granite base is increased to reach 98.4 % as in table 6-4 and (Fig 6.11)**.**

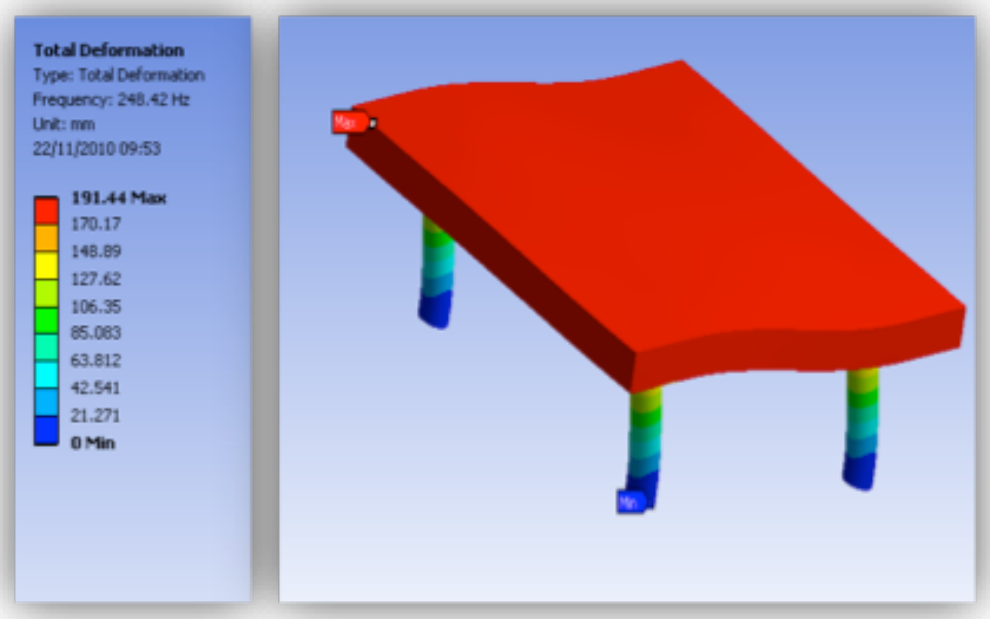


Figure 6.11: Optimised granite base.

Table 6.4 - Correlation of optimised gantry base.

FEA Model (Hz)	Hammer Test (Hz)	Accuracy (%)	Error (%)
526.36	518	98,4	1,6

After achieving a satisfying level of harmonic response (Natural Frequency) correlation between the FEA model and prototype, the next step will involve connecting all mechanical components to the structure and using the accelerometers to measure the vibration of the system while spindles and motors are running. In this case, the software will read and recognise the response of the system as acceleration. These readings will be used in the FEA model again to give the model an actual and more realistic response to excitation of the actual system during the test.

Afterward, generated data from the modified model will be used in a new simulation aimed at calculating the actual displacement of each part in the system. Completing these tasks will provide a solid and trusted database and information on the performance level of the system. At this stage, a new configuration (Z,Y) is added to the system, allowing the module to perform machining processes in two directions. In order to test the performance of the new axis, a milling machine was dispensed using the installed CNC control system.

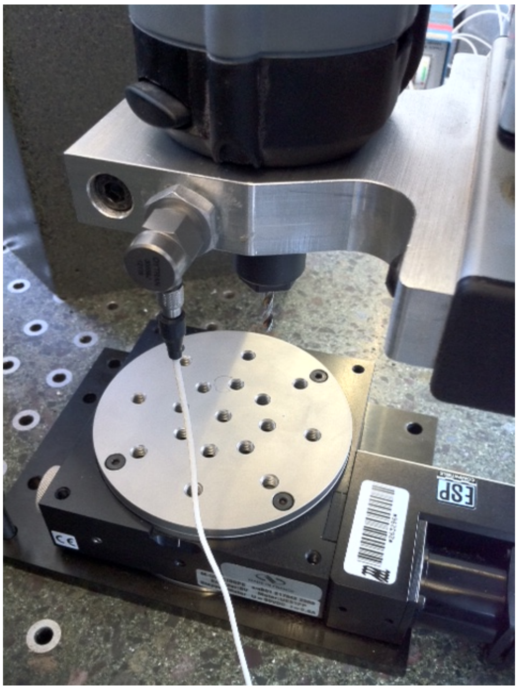


Figure 6.12: Rotary stages configuration with a spindle attached.

An accelerometer was then attached to the new configuration in order to detect its performance by measuring the acceleration in four different positions.

1. Spindle
2. Gantry (Side)
3. Gantry (Back)
4. Hexagonal Module

The results of the experiment are shown in the following table:

Table 6.5 - Readings from four different positions of the accelerometers.

	Acceleration (Measured in G)			
Spindle Speed (rpm)	Z-Spindle	Gantry (side)	Gantry (Back)	Hexagonal
10,000	3.2	0.2	0.62	0.79
12.600	3.3	0.08	2.21	2.07
18,000	3.4	0.28	0.75	0.26
21,000	3.1	0.225	1.36	0.22
25,000	4.3	0.86	1.54	0.59
30,000	4.32	0.06	2.02	0.4

The above results show that running the spindle in various speeds between 10,000 rpm and 30,000 rpm is causing a linear increase in the system's vibration. However, the system's performance can still be improved by reducing this vibration. This can be achieved by applying several design optimisation techniques described at a later stage.

6.2.3 Experiment 3: Measuring and Analysing Damping and Static Loads

The aim of this experiment is to assess the performance of the structure after attaching a selection of mechanical components to the system. This experiment consists of three parts:

1. **Damping test:** This test will be performed in order to identify the damping performance of the structure caused by the assembly technique of these parts (Joints, Fixation points, interface etc.), also called "Friction Damping". Based on the outcome of this test, modifications and adjustments can be applied to the system in order to improve the overall performance during the optimisation stage.

2. **Static Deflection Test:** this part will analyse the deflection of the structure caused by adding mechanical components and extra loads.

3. **Dynamic Deflection Test:** after adding extra parts and loads to the system, this test will re-assess the performance of the system at a certain stage where spindles are running before performing any machining process.

Experiment Set-Up

A number of new devices will be used in this experiment, including a Capacitance Displacement sensor (CDS), which will be placed on the top of an optical table to ensure it is level with a flat surface (fig.6.13).

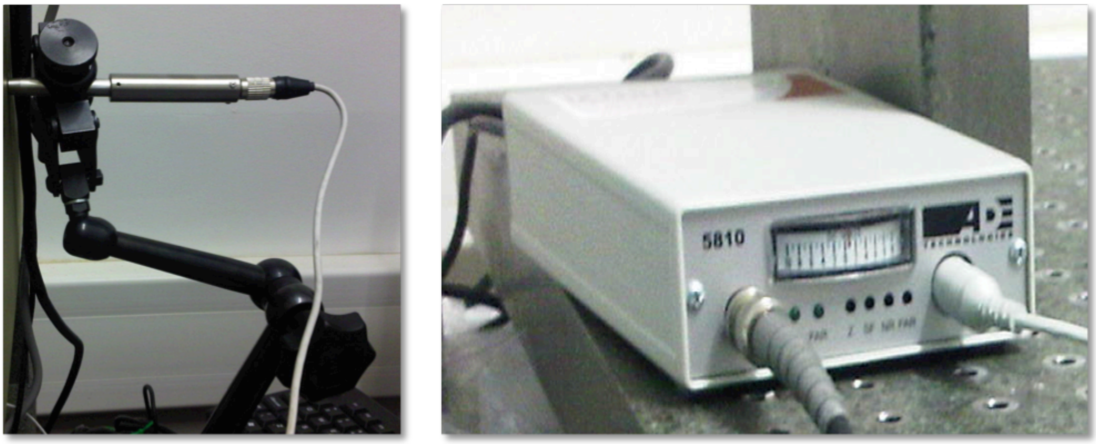


Figure 6.13: Capacitance Displacement sensor (Left), Gauge Module (Right).

Once the CDS is set-up, it will be connected to a Gauge Module (G.M) that will read the signal from the CDS in order to calibrate the device and send the DC-signal -in Volte unit- to the Data Acquisition Card (DAC). This will pass the relevant information to the PC in order to be analysed using LabView. This configuration will be used to read and analyse the data in each one of the above-mentioned tests. Each test will be performed five times in order to generate more accurate results.

Test 1: Damping

Using the Hammer-Test Method, the reaction of the structure will be tested in two positions in order to calculate the friction damping caused by using the current fastening and assembly methods. The generated signal from knocking the (aluminium Gantry) structure with the hammer will be read and analysed by LabVIEW, with an applied force in both positions is measured to be 100N.

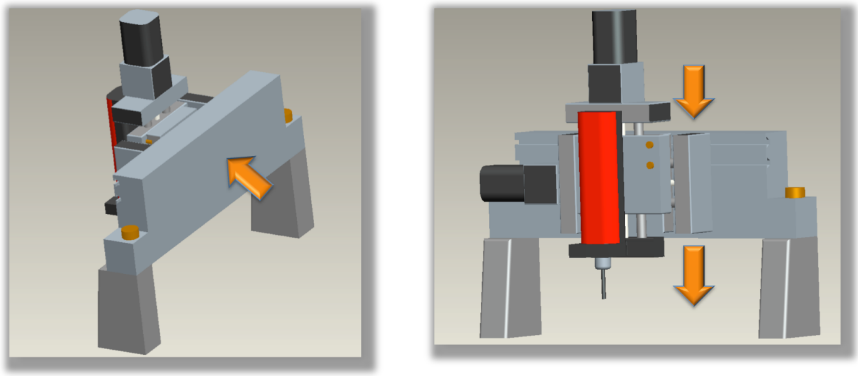


Figure 6.14: Damping test, horizontal (Left), vertical (Right).

The results showed a deflection of (<1μm) when the gantry is knocked from the top (vertical damping), while the structure deflected by (<2μm) horizontally when the gantry was knocked from the rear. Having the aluminium gantry placed vertically on top of two granite supports, which creates a higher resistance and damping force from the structure to be deflected vertically, can justify this (fig. 6.14). While in the second mode, the gantry is not fixed to any other parts horizontally, which means there is no resistance or damping to reduce the deflection.

Test 2: Static Deflection

As shown in previous static analysis of the Gantry structure, the weakest point where the maximum deflection happens is in the middle of the gantry. Therefore, the Z,Y configuration including the spindle is placed exactly in the centre of the gantry in order to generate maximum deflection, which will result in a more reliable result.

This test aims at measuring and analysing the static deflection of the structure when applying loads while the spindles are not running. Therefore, it will allow simulating and modelling the system's behaviour when different mechanical components are considered in the future, including geometries, weight and fastening methods. The first stage of this experiment will measure the deflection of the structure when attaching only the mechanical components. The second stage will re-measure the deflection after adding extra weight on the structure as shown:

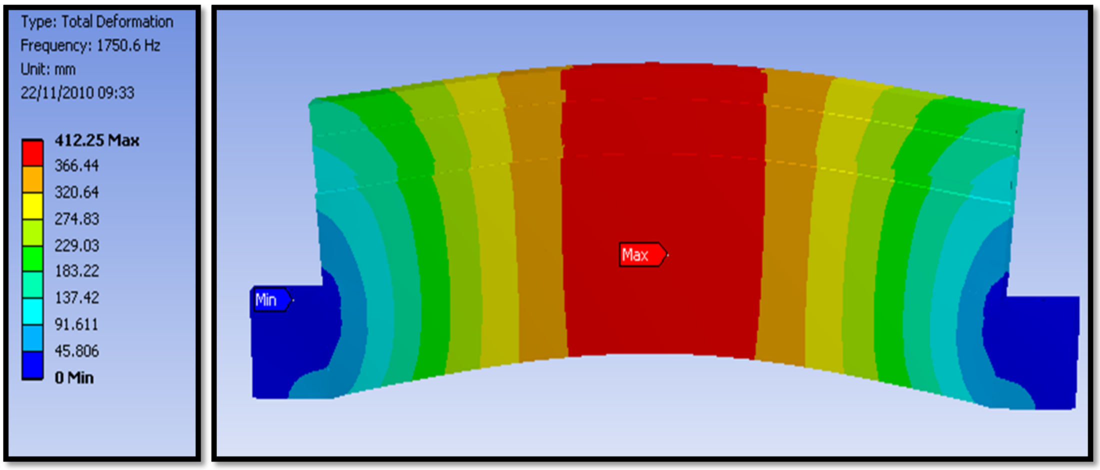


Figure 6.15: Static analysis, maximum deflection shown in the centre.

This consideration means placing the Z,Y configuration within an equal distance from the granite supports as in figures 6.15 and 6.16. This step is performed using a control system (CNC-Based) in order to ensure achieving an accurate and measured positioning process.

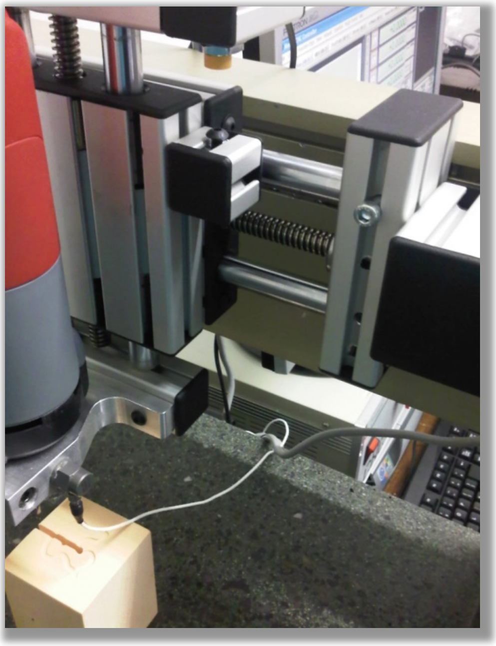


Figure 6.16: Z,Y configuration placed in the centre.

- **Stage 1:**

Mechanical Components = 9 Kg

Load applied = 0 Kg   Total = 9 Kg = 88.25 N

Readings in µm	1	2	3	4	5	Average
	0.056	0.058	0.056	0.057	0.057	0.0568

- **Stage 2:**

Mechanical Components = 9 Kg

Load applied = 10 Kg Total = 19 Kg = 186.32 N

Readings in µm	1	2	3	4	5	Average
	0.062	0.063	0.062	0.063	0.061	0.0622

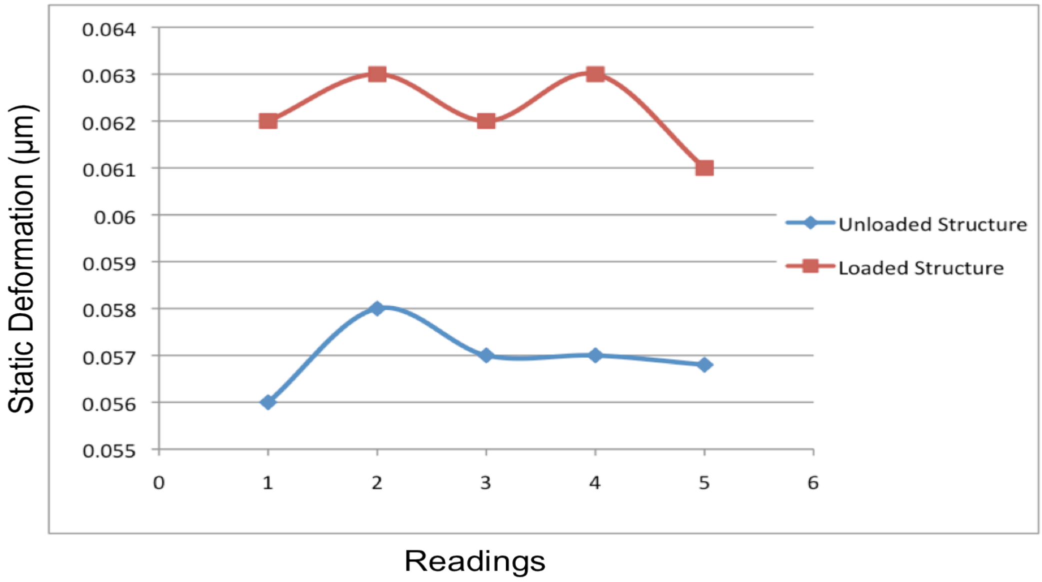


Figure 6.17: Static deflection assessment results.

Figure 6.17 provides accurate results of the gantry structure static deformation when applying two sets of loads. First, when mechanical components are attached to include positioning stage, spindles and motors, a minimal deflection of 0.0568 µm occurred. When extra weight (10 kg) was added on top of the gantry structure, this static deflection increased to reach an average of 0.0622 µm. These results confirm the robustness of the gantry structure when loaded vertically (Z-direction).

Test 3: Dynamic Deflection

In this test, the deflection of the structure will be measured as in test 1 and 2 while the spindle is running at 6 different speeds. Therefore, extra forces need to be considered in this test including the rotation and out-of-balance force caused by the spindle running at various speeds.

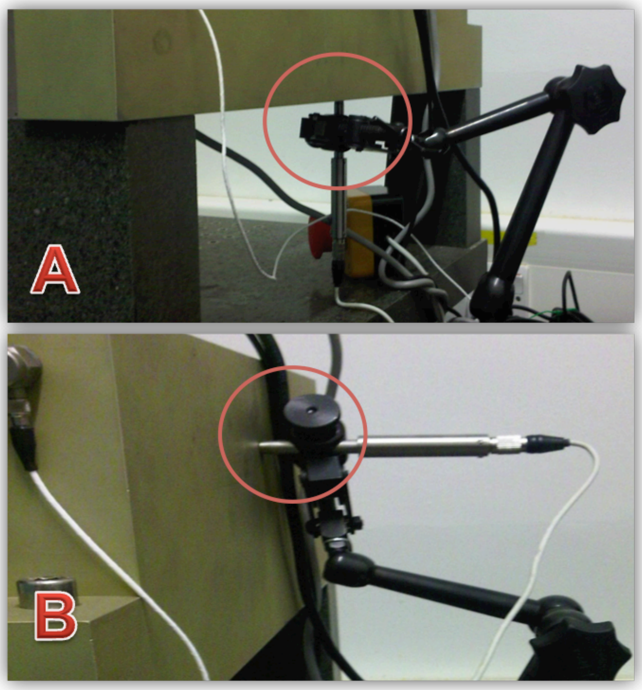


Figure 6.18: Probe positioned at the Base (A) and the Back (B) of the Gantry structure.

Table 6.6 - Deflection in (μm) using accelerometers.

Speed (rpm)	CDS Probe Position			
	Gantry Back Deflection (μm)			
	1	2	3	**Avg.**
10,000	2.922	3.01	3.01	**2.98**
12,600	2.801	2.991	2.901	**2.89**
17,000	3.01	3.12	3.02	**3.03**
21,000	3.01	2.98	2.91	**2.96**
25,000	2.254	2.338	2.102	**2.53**
30,000	2.101	2.202	2.30	**2.20**

As in test 1, the CDS probe will be positioned in two different positions; the first position is at the back of the gantry to measure the horizontal deflection, and the second is at the base of the gantry to measure the vertical deflection as in figure 6.18.

According to measurements from the back of the gantry, the displacement has been measured several times in each speed in order to ensure more accurate results as in table (6-6).

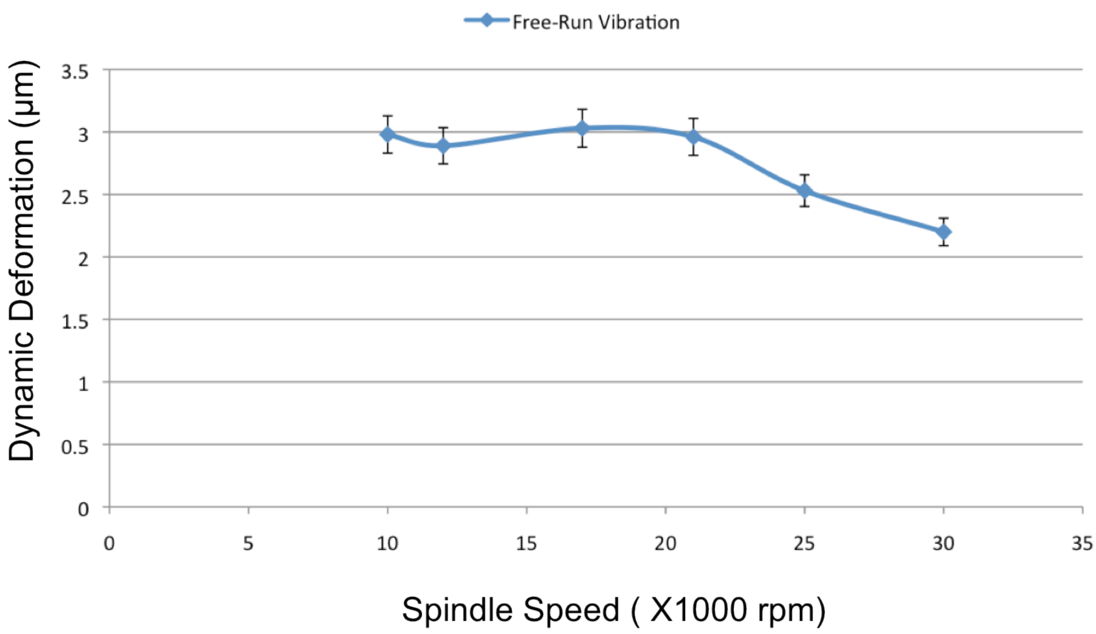


Figure 6.19: Spindle's Free-Run dynamic deformation.

Therefore, when the spindle runs at a speed of 30,000 rpm, it generates a maximum displacement in both vertical and horizontal modes. However, the deflection from the base of the gantry can only be measured by nanometres due to the robust structure of the gantry and granite supports (fig. 6.19). The next step will focus on measuring the displacement of the system while machining processes are being performed (drilling and milling).

6.2.4 Experiment 4: Displacement Measurement and Analysis

The aim of this experiment is to provide accurate and real-time vibration and displacement measurements of the entire system. In order to perform this experiment, modifications need to be done regarding both set-up and measuring techniques. This process includes, adding more accelerometers to cover various positions in the cell and adding extra machining spindles to the system in order to have two running spindles at same time. Three accelerometers will be used in each test, and the signal received from each accelerometer will be read in a form of acceleration (A) using LabVIEW. The next step is to convert the provided readings to displacement (D) in micrometers (μm). This can be done using mathematical equations as in (i);

$$D = \frac{70.4X10^{5}XA}{CPM^{2}}$$

Where:

D : Vibration displacement. (μm)

A : Vibration acceleration. (G)

CPM : Cycles per minute. (RPM) (Klubnik, 2009)

Figure 6.20 shows positions where the accelerometers are located in the cell. Positions 1 and 3 are covering the machining contact points where tool tips are contacting with the machined part. Position 2 is dedicated to measuring the vibration of the granite base resulting from performed machining processes by the gantry and hexagonal modules. This position is important when considering the effect of running spindles and performed machining processes on the tool holding fixture that will be positioned on the granite base.

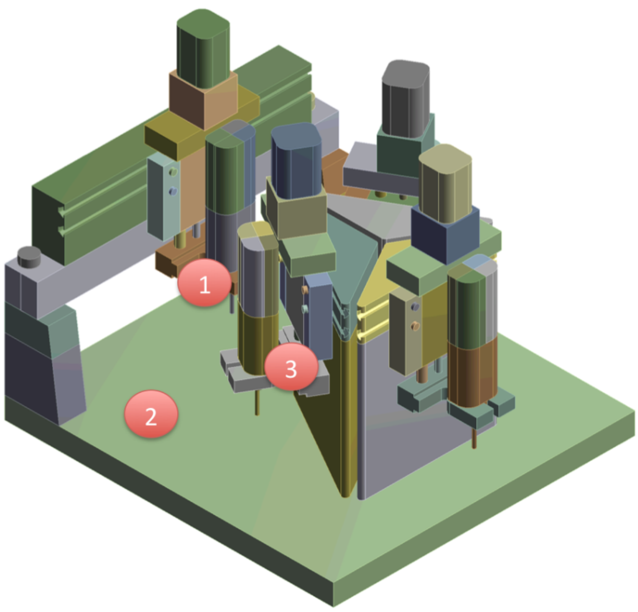


Figure 6.20: Accelerometers positions.

Each test will be performed several times; one of which to measure the vibration of the system when two spindles are performing drilling and milling machines. The purpose of this step is to measure the deflection of the gantry in X and Y directions. Other experiment settings include running spindles with a speed of 30,000 rpm in order to machine a cube of ABS (Plastic material).

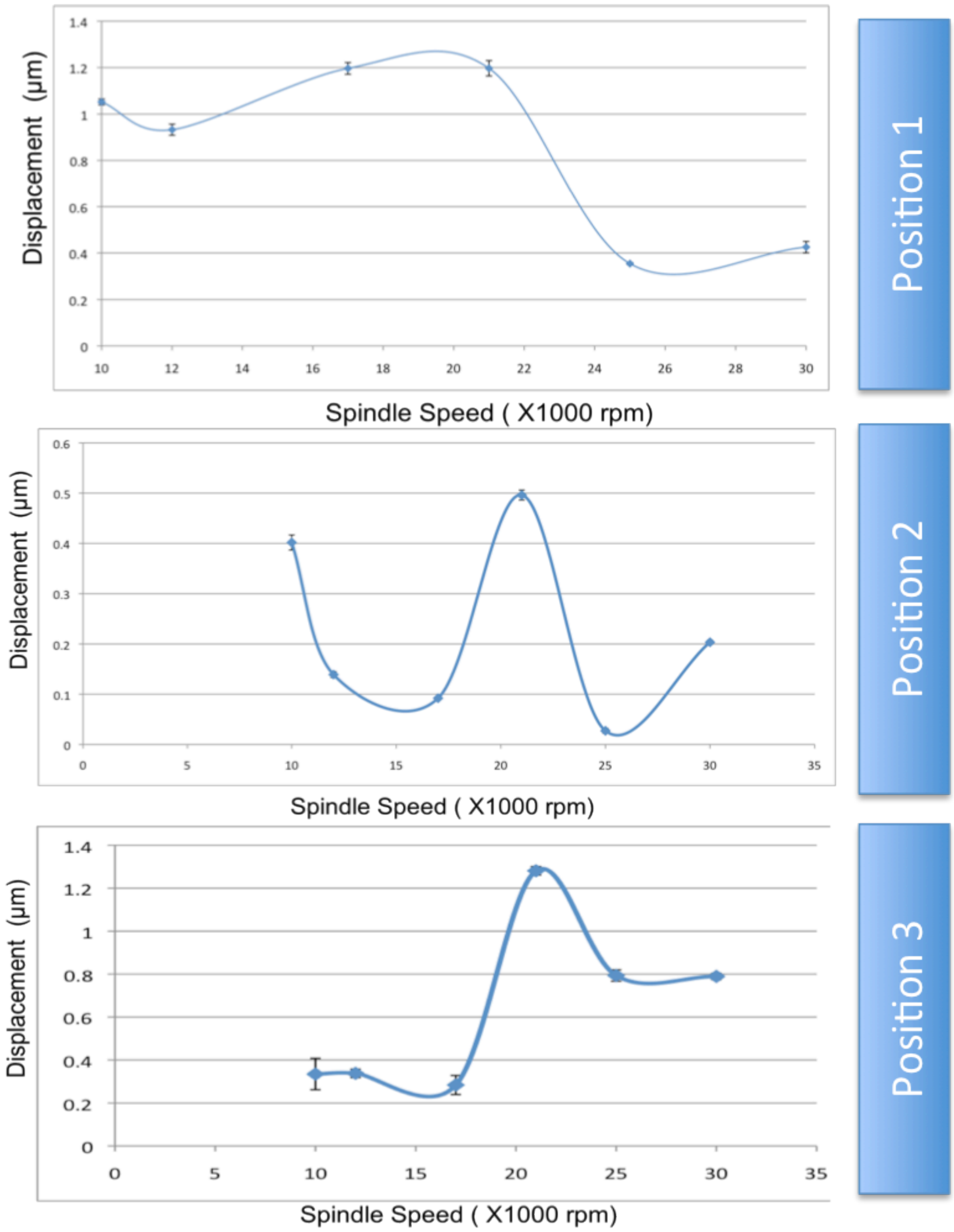


Figure 6.21: Structure's displacement in three positions during milling and drilling machining processes.

The above figure (6.21) provides an overview of the reaction of the entire system during any machining process. Results show that the base is the least vibrated part of the system. This can be justified by having no direct contact between the base and any running spindle. Also, it shows that the rate of displacement is increasing when performing a milling process compared to drilling. Moreover, the experiment validates the conceptual model regarding dynamic displacement of the gantry when the part reaches the fundamental frequency mode.

6.3 Summary

Following the design methodology from chapter 3, this chapter has reviewed the performance of the conceptual and physical model of the RMC. This process included an introduction of several tools and components that have been used in the assessment process of both models. Also, it has provided a correlation process in order to develop an optimised FEA model of the design.

Overall, the results of both conceptual and physical models are considered satisfactory, since the aim of developing a prototype in this project is to demonstrate a novel design with maintaining a satisfactory performance of the prototype. The assessment process indicated room for improvement regarding design, structure and performance. Therefore, the next chapter will focus on the issue of optimising the current model by applying an optimisation methodology as part of the design process in this research.

Chapter 7:

Design Optimisation Methodology

Chapter 7 - Design Optimisation Methodology

7.1 Introduction

Reviewing several design concepts, in order to select a concept with the potential to deliver the required performance and satisfy the objectives of this research, has been shown in previous sections of this research. This process resulted in building a physical model based on several design iterations and stages, including a material and components selection with assembly and assessment processes. This section will focus on the third stage of the design framework of this research (fig. 7.1) by providing possible solutions to optimise the design. This aims to improve the overall performance of the system and present better design and prototyping methodologies to build even more efficient and utilised Reconfigurable Micro-manufacturing Cells in the future.

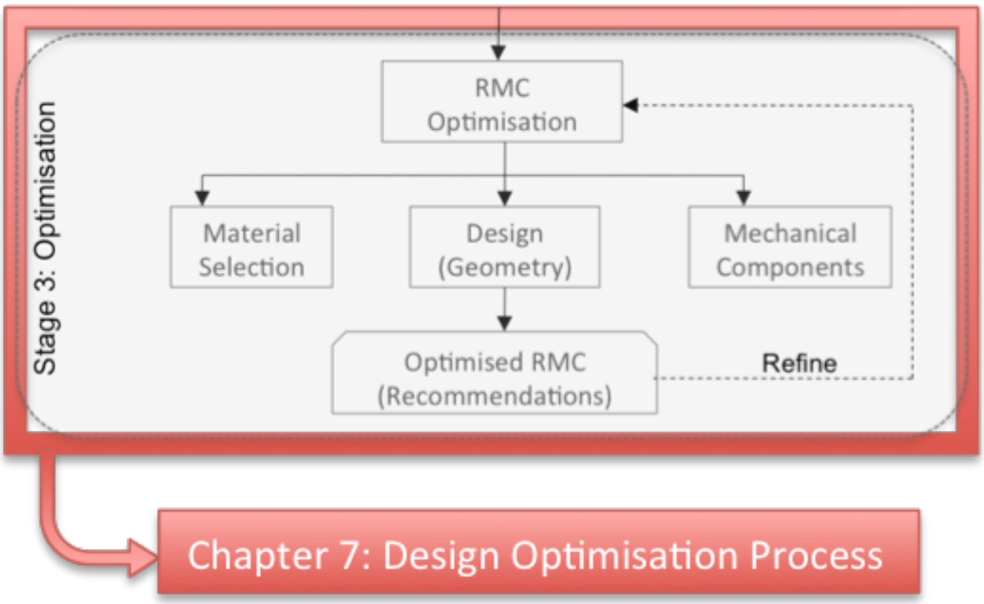


Figure 7.1: Third stage of design methodology.

This process starts by reviewing the development of the design optimisation process over the past few decades, outlining some of the well-known methodologies and techniques that have been used to optimise and improve industrial designs. It also, highlights some of the tools found in this research; which are used to perform such a process. Following this, an optimisation process of the current concept based on the current performance of the system will be delivered, providing possible solutions to improve the performance of the system.

7.2 Machine Design Optimisation: An Overview

Following the success of structural optimisation processes in the 1970s, which originally started in the late 1960s by Schmitt, has encouraged the implementation of Multidisciplinary Design Optimisation process (MDO). According to (Avriel et al, 1979), MDO can be defined as "a field of engineering that uses optimisation methods to solve design problems incorporating a number of disciplines ". Following that, the industrial optimisation field has progressed dramatically after including several analysis and problem solving tools in order to cope with the increased complexity of modern product design processes and market demand. Mainly, such an approach aims at increasing the quality of product as well as minimising the production cost (Cramer, 1994).

In general, classic design process usually involves optimising any proposed design based on changing the geometry in order to come up with various design iterations in order to develop a number of suitable engineering solutions. Moreover, developing an optimal design requires the consideration of a large number of design variations. Therefore, the dedicated resources to fulfil such as time and cost would be considered insufficient as a business model.

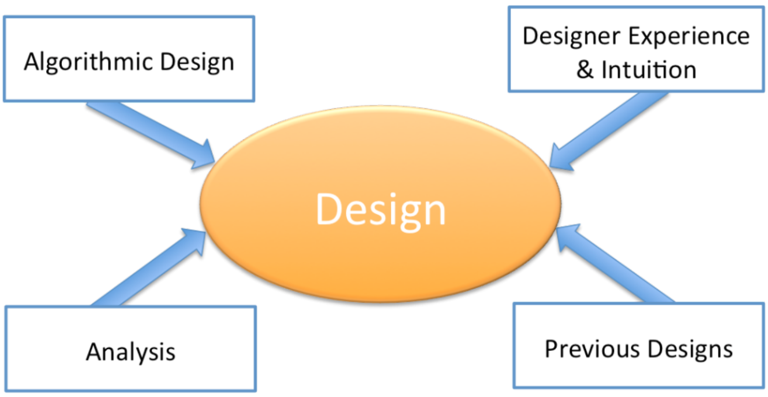


Figure 7.2: Components of explorative design process (Clune, 2009)

Firstly, design optimisation processing requires identifying what should be optimised, and what the design variables are; including the quantities or parameters that can be changed in order to achieve an optimum design. As fig. 7.2 shows, the optimisation of any design is based on several criteria such as design objectives, previous design's limitations and analysis.

Furthermore, design optimisation applications tend to be numerically intensive because they must still perform the geometrical and analytical iterations. Therefore, most design optimisation problems can be identified as a mathematical optimisation problem. In this project, the main focus is on the design optimisation of the theoretical and physical aspects within the system including, mechanical parts, assembly techniques and material selection. It should also include the system re-configurability, flexibility and productivity levels.

7.3 Design Optimisation: Methodologies and Tools

The optimisation process of product designs has been developed over the past few years, driven by the vast improvement in Computer Aided Design (CAD) and Finite Element Method (FEM) tools (Akira, 1999). This combination of computing hardware, software, human interfaces, and network connectivity has evolved tremendously. The integration of optimisation techniques with Finite Element Analysis (FEA) and (CAD) is having pronounced effects on the product design process. This integration has the power to reduce design costs by shifting the focus toward the engineer's creativity.

Furthermore, tools such as CAD/ CAM and FEA made it possible for concepts to be developed as part of the design process of each part, limits of analytical tools, manufacturing capabilities, and acceptable lifecycle costs (Knight et al, 2002).

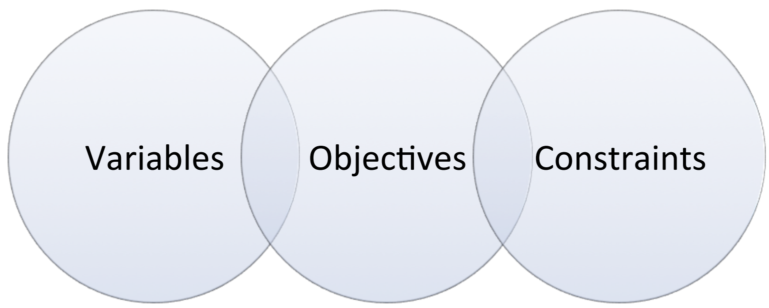


Figure 7.3: Problem formulation in design optimisation process (Cramer et al, 1994).

Moreover, several design optimisation and quality control methodologies have benefitted from these modern tools including well-known methods such as: Topology optimisation, Taguchi, Approximation and other optimisation methods (Simpson, 2004). However, most of these methods are based on performing simple problem evaluation procedures, consisting of three main steps, first generating a three-dimensional geometry of a part or assembly. The second step involves developing a finite element analysis model of that part before evaluating this model based on a previously determined set of criteria (fig. 7.3).

A design variable: is a specification that is controllable from the point of view of the designer. Design problems with continuous variables are normally solved more easily. Also, these variables are often limited in that they often have maximum and minimum values. Depending on the solution method, these boundaries can be treated either as constraints or separately. A constraint is a condition that must be satisfied for the design to be feasible. Finally, an objective can be defined as a numerical value that is to be maximised or minimised which is also considered as a target to be reached.

7.4 Design Optimisation of RMC: Geometry

The process of optimising the RMC design in this part will focus on improving the performance of the main structure of the system. Therefore, two main modules are considered during this stage, gantry structure and Hexagonal structure as shown in fig. 7.4.

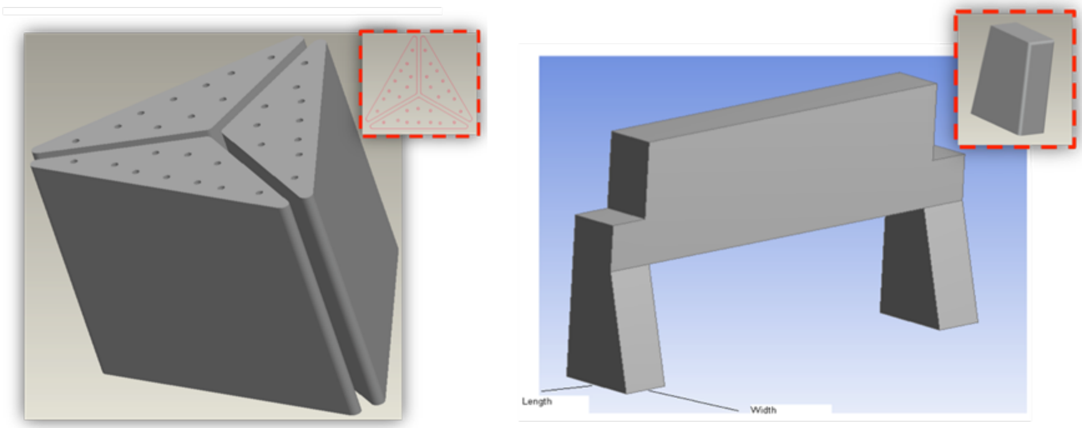


Figure 7.4: Optimisation of two modules within RMC.

The selection of these two parts was due to their influence on the operational performance of the cell, as they hold and directly connect with the mechanical components in order to perform machining processes. Also, the performance assessment process from the previous chapter showed that the gantry structure represents the weakest point of the structure. Therefore, it is necessary to improve the performance of the gantry by modifying the geometry of the granite supports.

Certain constraints however must be considered before performing the optimisation process of the RMC including, maintaining the length and design of the aluminium part of the gantry in order to maintain the machining-envelope of the cell. Also, another constraint involves applying the same fastening methods that hold positioning stages and spindles to the main structure. A similar approach is used with the hexagonal module, as it requires maintaining the same length in order to be able to accommodate linear stages and mounting aluminium parts.

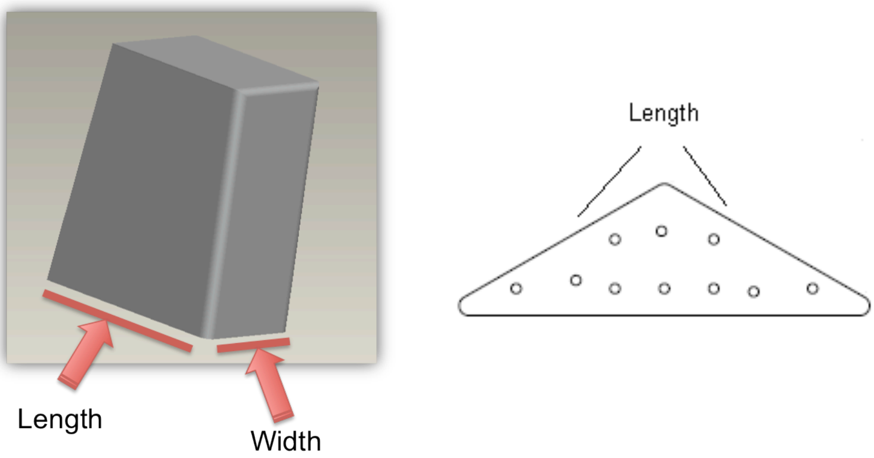


Figure 7.5: Geometry optimisation of two supports and hexagonal part.

The process of geometry optimisation will be based on generating a variation of lengths and widths of the supports. Meanwhile, the length of two of the hexagonal part sides will be modified in order to observe changes in performance (fig. 7.5).

7.4.1 Gantry Supports Optimisation Process

Initially, this will involve developing a range of design parameters based on combinations of lengths and widths representing new geometries of the supports. In addition to the current configuration of geometry, eight other design parameters (DP) will be examined in the next part providing an idea of how this part will perform when each DP is applied in the future. This process allows an improved RMC design to be developed in the future once all parts are optimised.

Table 7.1 - Design parameters of the gantry supports:

Design parameter	Width	Length
Current (DP0)	95	60
DP1	90	60
DP2	100	60
DP3	105	60
DP4	110	60
DP5	115	60
DP6	95	55
DP7	95	65
DP8	95	70

The first step is to measure the static deflection of the design for each design parameter, by applying a vertical force of 500N on the top surface of the gantry. Table 7-1 shows the relationship between the static deflection and design parameters. It is noticed that increasing (from DP2 to DP 5) and decreasing (DP 2) the geometry of the width does not affect the static deflection significantly as it remains linear from DP 0 to DP 5. In contrast, varying geometry of the length can influence the deflection dramatically as can be seen in figure (7.6), where the deflection reduces from 0.26 μm to 0.24 μm and 0.22 μm by increasing the length of 5mm from original of 60 mm in DP7 and DP8.

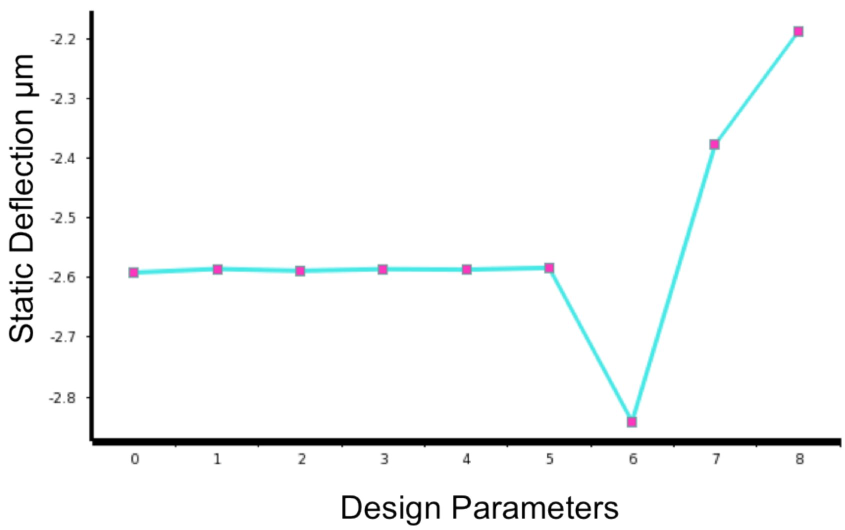


Figure 7.6: Static deflection of nine design parameters.

This indicates that the length is a more sensitive parameter than the width for stiffening the gantry. The second test involves calculating the equivalent stress of the structure for the same design parameters as shown in fig. 7.7. The results of the simulation show a significant decrease in the stress of the structure when increasing the length. This can be rectified by increasing the volume and cross-sectional area of the supports as the length increases accordingly.

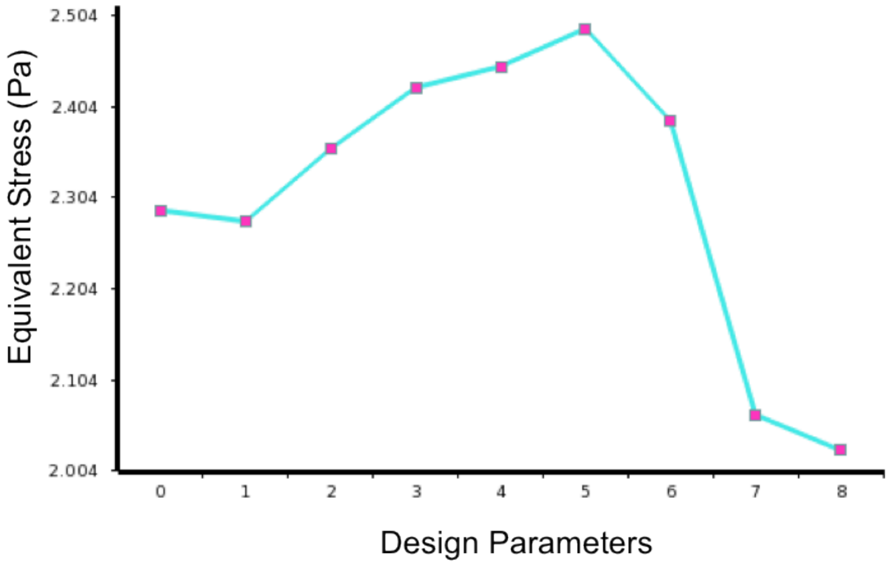


Figure 7.7: Equivalent stress of nine design parameters.

The following section will examine the effect of modifying the structure's geometries on the dynamic performance. The transient analysis focuses on the forced vibration that could be created during any machining process by the force caused from running spindles. In order to study the forced vibration, a force was applied on the top surface of the gantry with a magnitude of 50 N and with frequency of 500 Hz. Fig. 7.8 shows the relationship between the dynamic deflection and design parameters. It can be observed that both decreasing the length and increasing the width can reduce the dynamic deflection.

This is due to the change in geometry, which affects the natural frequency accordingly. The driving frequency 500 Hz is closer to the underlying natural frequency of the gantry. As a result of this, both decreasing the length and increasing the width can reduce the dynamic deflection.

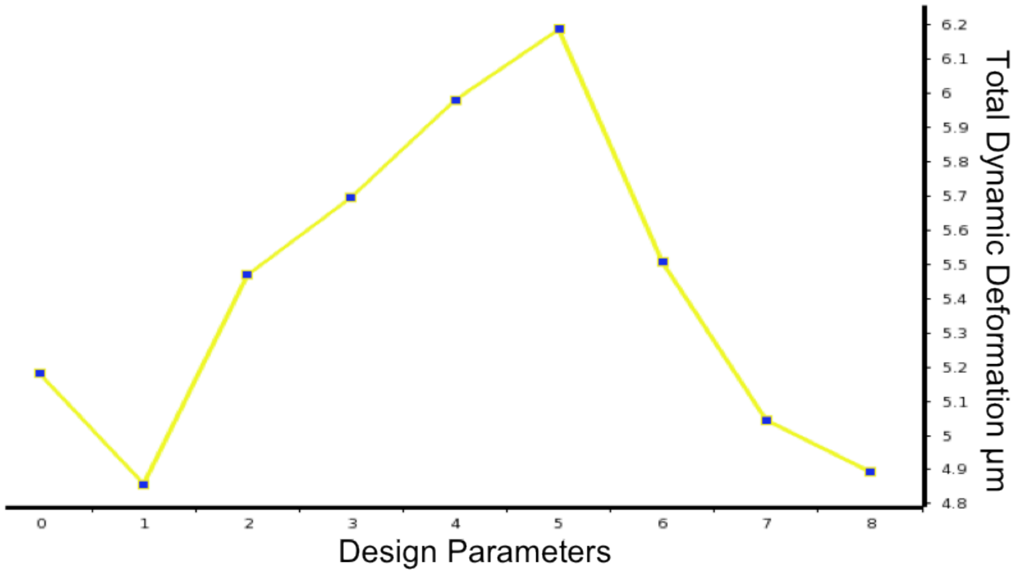


Figure 7.8: Dynamic deformation at 500 Hz driving force.

In order to avoid this problem and develop a more trusted model, the driving force needs to be reduced in order to avoid upsetting the structure, as running a 500 Hz force is considered a close value to the fundamental natural frequency of the structure. Therefore, the force is reduced (200 Hz) below the natural frequency range of the structure (300 Hz). The results shown in (fig. 7.9) indicate that increasing the length and width of the structure will effectively reduce the dynamic deformation.

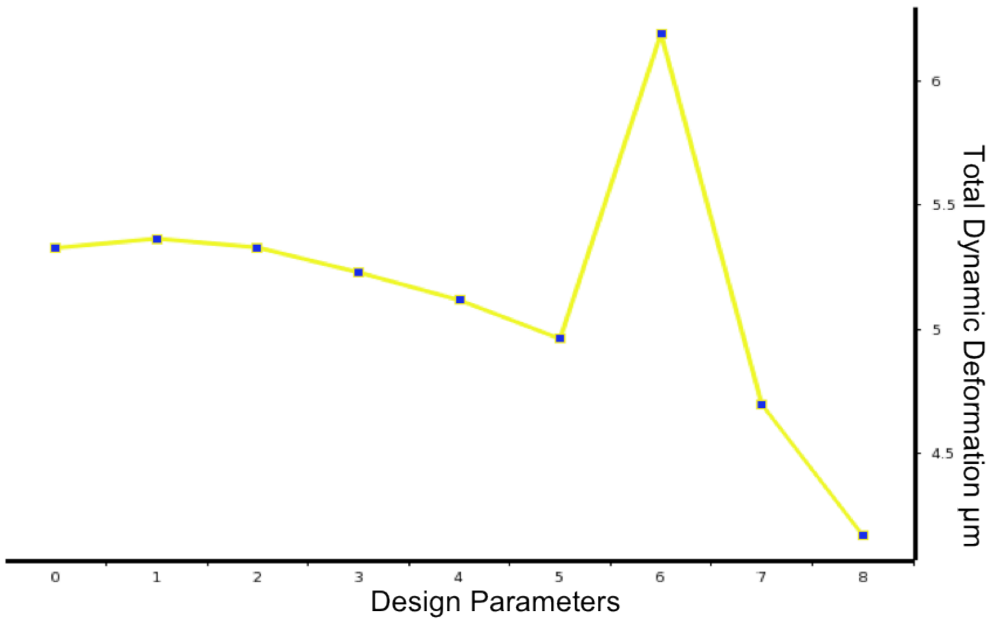


Figure 7.9: Dynamic deformation at 200 Hz driving force.

In order to optimise the geometry of the existing gantry supports, the optimised model must satisfy two objectives: minimising the static deflection and dynamic deflection. Each gantry support has a base length of 104.5 mm and width of 66 mm. The optimisation simulation suggests three optimisation options as shown at Table 7-2. All three options can reduce the static and dynamic deformation.

Table 7.2 - Three suggested design optimisation options for gantry supports:

	Length (mm)	Width (mm)	Static Deformation (m)	Dynamic Deformation (m)
Objective	No	No	Minimise	Minimise
Option A	103.65	65.779	2.3435 E-7	4.4889 E-8
Option B	97.565	65.873	2.3398 E-7	4.5331 E-8
Option C	91.485	65.685	2.3472 E-7	4.5888 E-8

The following section will apply similar optimisation methods on the other part of the RMC, which is the hexagonal module. As mentioned earlier, the sides of the module will be modified in order to test the performance of the part once changes in geometry have been applied. The weakest stiffness point of this part is identified when a force is applied on the top surface horizontally as shown in Fig. 710.

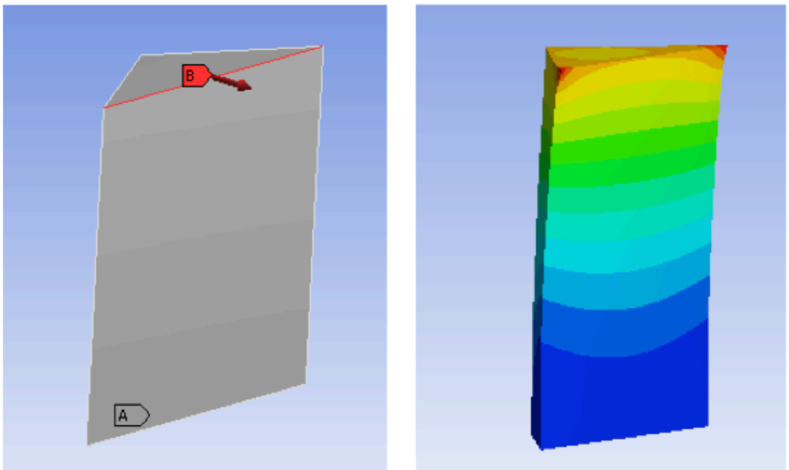


Figure 7.10: Applied force on the structure.

Therefore, even when the static and dynamic deformation are currently considered within a good range when applying forces or performing machining process, any applied forces that may act on this part should be considered in order to avoid any design failure when new machining conditions are applied in the future. The length will vary from 132 to 153 mm with 5 mm increment (currently 137 mm).

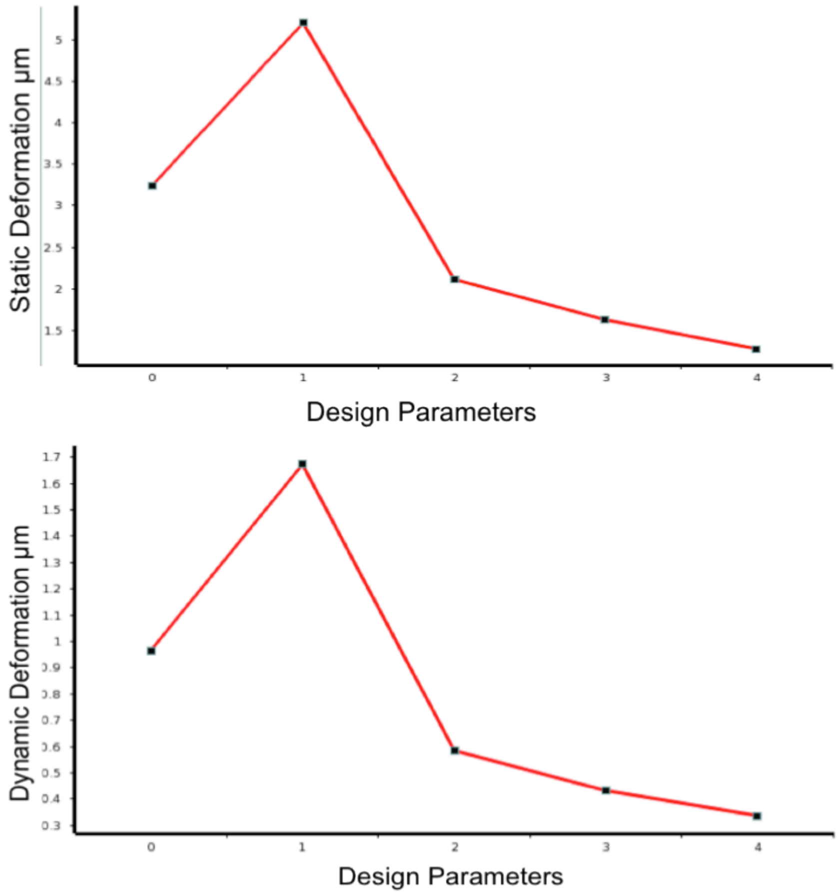


Figure 7.11: Static and dynamic deflections of the structure.

Both static and dynamic deflections created a similar trend, indicating that increasing the length of the sides of the structure will reduce the value of deformations. This can be traced back to the increase of the structure's stiffness that results from an increase in volume and contact area with the applied force.

Table 7-3: Static and Dynamic deformations of five design parameters.

Design Parameter	Length (mm)	Static deformation (m)	Dynamic deformation (m)
Current (DP0)	136.96	3.24278850047164E-07	9.66120319541852E-07
DP1	132	5.20321551988908E-07	1.67236812599109E-06
DP2	143	2.11279147649536E-07	5.85137393751995E-07
DP3	148	1.62600548926726E-07	4.32713674317207E-07
DP4	153	1.27963831954173E-07	3.37036280400501E-07

Table (7-3) provides detailed value calculations of static and dynamic deformations, showing clearly the reduction of their values. Based on performing the assembly stage in this project, it has been noticed that expanding the size of the RMC base (footprint) can be considered in the future. This change in the cell's footprint can be proved significant as different types of mechanical components and sub-systems may be added to the RMC as part of the optimisation process to increase the system's productivity. This feature can also be a key to adding more processing modules to the RMC as part of the utilisation requirements.

As seen in (fig. 7.12), Dutta (2000) it is stated that increasing the number of modules within a production could affect its production rate (unit/day). Also, the cost of producing (units/cost) is decreased substantially after a small increase when implementing this approach.

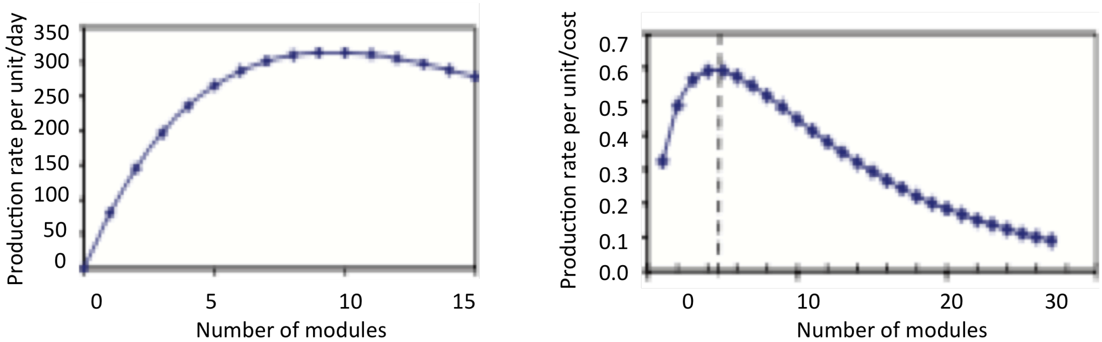


Figure 7.12: effect of increasing the number of modules on production rate and cost (Spicer, et al, 2002)

7.5 Design Optimisation of RMC: Material Selection

Material selection is another optimisation criteria, which can be used to achieve a better design for the RMC. Three choices of material were considered in this section in order to compare the performance of the structure using each material, assuming that the entire structure will be built using one material, only unlike the current prototype, which contains a mixture of material assembled together as modules within the RMC.

Structural Steel, Aluminium alloy 6082 and Industrial Steel were used to analyse the gantry based on the optimised geometry of the width and length. Figurers 7.13 and 7.14 show the static and dynamic deformation of the gantry made from Aluminium alloy 6082. The comparison among three materials is listed in Table 7-4.

Table 7.4 - Static and Dynamic deformations of five design parameters.

Material	Static deformation (m)	Dynamic deformation (m)
Structure Steel	2.3472 E-7	4.5888 E-8
AL alloy 6082	6.6235 E-7	1.3083 E-7
Steel	1.258 E-7	2.614 E-7

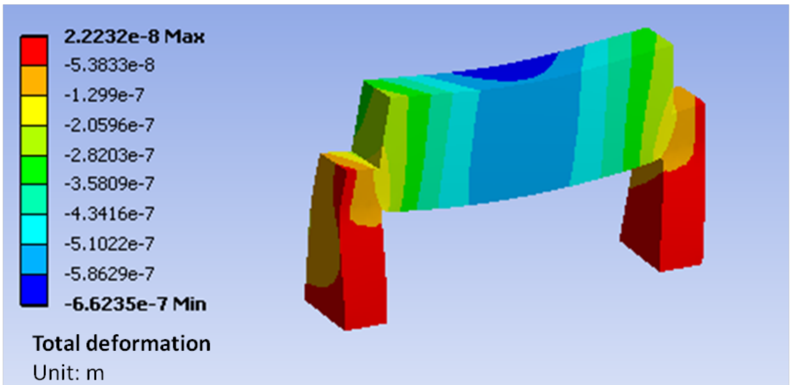


Figure 7.13: Static deformation of AL6082 gantry structure.

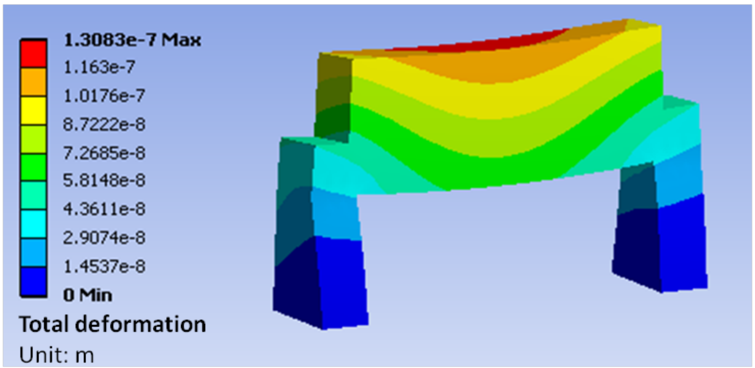


Figure 7.14: Dynamic deformation of AL6082 gantry structure.

7.6 Design Optimisation of RMC: Mechanical Components

As mentioned earlier in this research (chapter 5), several mechanical components have been added to the RMC in order to test the operational performance of the cell when machining processes are performed. Overall, by considering the applications of the mechanical components within the RMC, there are three main tasks needing to be performed including these components: holding machined parts (fixture), positioning machine tool heads (linear stages) and performing the actual machining process (spindles).

Selecting new mechanical components will focus on improving the machining capability of the prototype, which means that components such as linear stages and machining spindles must be upgraded in order to achieve better operational performance. Thus, each component will be upgraded based on certain criteria. First, new machining spindles must achieve better machining accuracy, which requires higher machining speed, minimised vibration and the ability to make use of smaller tool tips. Second, linear stages are required to be lighter and smaller to reduce the load applied to the machine's structure as well as to increase the size of the work envelope. Also, these stages must provide more positioning accuracy in order to achieve better machining accuracy.

Based on these basic criteria, two new mechanical components have been selected off the shelf to optimise the performance of the RMC. The linear stage is shown in Fig. 7.15 is M-511 Nano-precision made by PI. Unlike the linear stages that are being used in the current prototype, this component is capable of achieving an accuracy level of 2 nm while offering a smaller size.

Figure 7.15: PI Linear stage model No. M-511.

On the other hand, selecting a machining spindle depends on increasing the machining speed and reducing the size. Based on that, a wide range of motor-spindles can be employed as part of the RMC in order to achieve better performance. For example, Nakanishi high-precision motor spindles (Fig. 7.16) come in various diameters and speeds, which allows for the performance of several machining processes such as milling, drilling and grinding. The selection of new mechanical components is considered a significant part of the optimisation process, since the specifications of each component will be used in a new optimisation model. Also, the optimised structure including new geometry and material will provide a new level of performance based on the applied changes of these design aspects.

Figure 7.16: Nakanishi High speed motor spindle.

Moreover, the data collected in the previous chapter will be used as a benchmark in order to optimise the performance of the current design. The aim of following the approach in machine design optimisation is to improve the performance of the RMC by taking advantage of the correlation between the FEA model and the prototype. This approach allows changing design parameters using FEA in order to reach a satisfying level of performance without the need to follow a trial and error technique. Therefore, this iterative approach is capable of reducing the required time and cost to optimise the design of the RMC. Furthermore, this optimisation methodology can be used as a tool to test the current design when any future modifications need to be applied, while considering the frequent changes in market demand.

7.7 RMC Optimisation Process

Based on the three main optimisation parameters in this section – geometry, material and components – a new model is developed following the same design assessment methodology as in the fourth chapter (4.3.1). The first step included generating a 3D model containing all the modified geometry, material and specifications of the parts. A meshed model was then produced before running a static and dynamic analysis of the new design.

According to Table 7-2, option A is considered a suitable choice to optimise the gantry supports, as it indicates minimising both static and dynamic deformations of the structure. On the other hand, the material optimisation process showed (Table 7-4) that aluminium alloy 6082 would perform better than other materials, such as structural steel and granite, when comparing the dynamic deformation of the structure using each material. Finally, the provided specifications of the new components (PI linear stage and Nakanishi spindle) suggest a better machining performance.

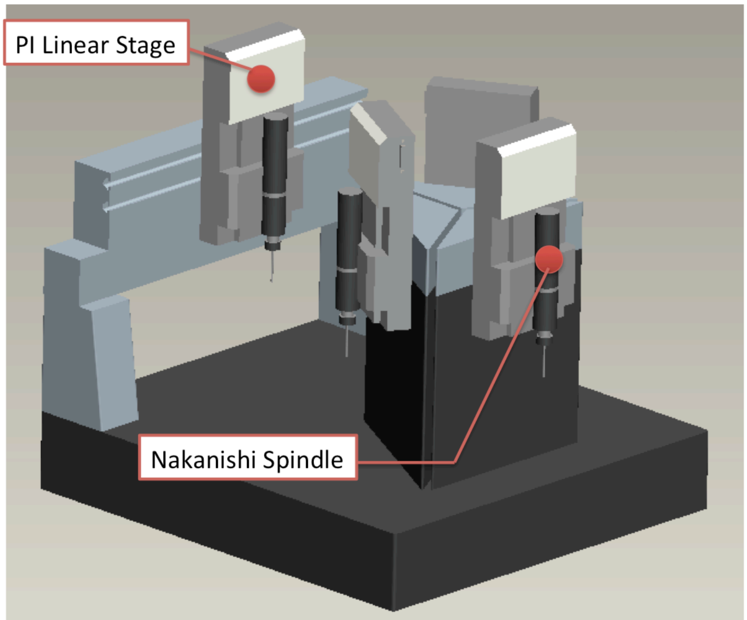


Figure 7.17: Optimised design of RMC.

Figure 7.17 shows a 3D model of the optimised RMC including the new mechanical components. Other optimisation features also include increasing the thickness of the granite base; applying new geometry and using aluminium material for both the supports and gantry structure.

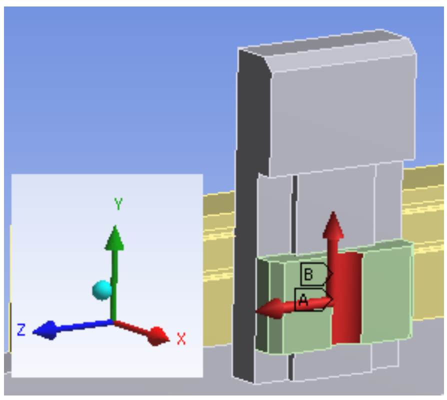


Figure 7.18: Applied force to measure the structure's harmonic response.

The above figure (7.18) shows another assumption that involves the assembly of linear stages within the RMC. In this model, all linear stages are considered fixed to the aluminium mounts of the hexagonal modules and gantry. This will result in axial force being applied to the linear stage as a result of performing the spindle rotation.

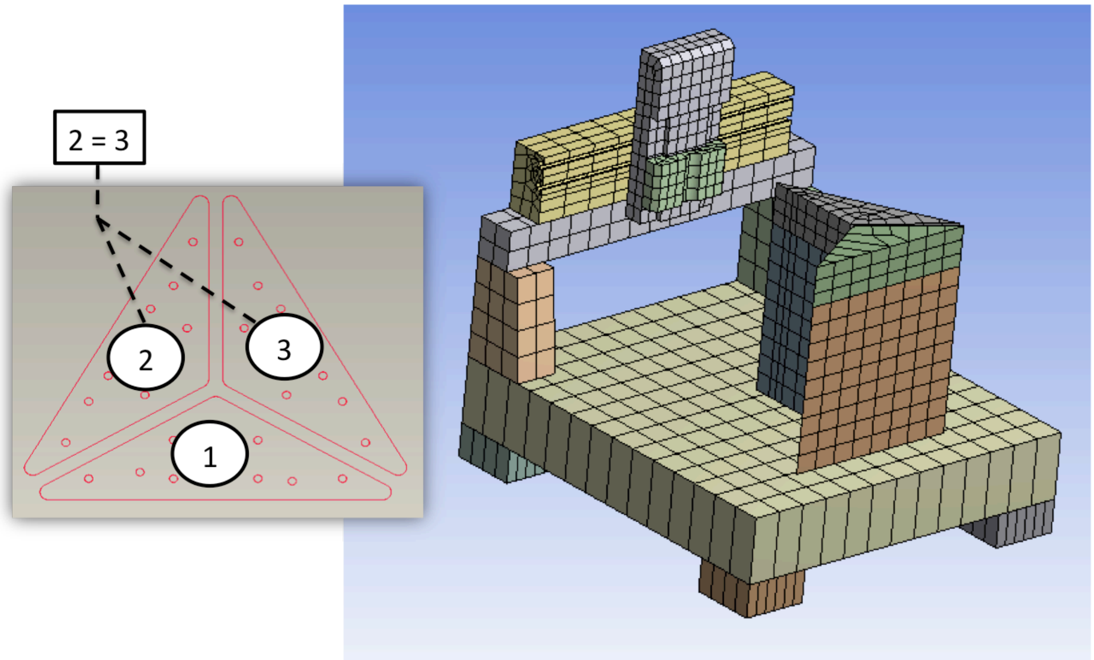


Figure 7.19: Mesh of the optimised design.

After generating a Mesh of the optimised model (fig 7.19), it is important to state all assumption and restricting conditions to clarify the analysis method of this design. Firstly, modelling the hexagonal module will perform on two of the three parts, because parts 2 and 3 have an identical geometry, positioning and fixation method. Therefore, the result of modelling any part of the two can be considered for the other. Secondly, the deformation of the structure will be considered as an Elastic deformation, which means a linear relation to the deformation and applied force.

Boundary conditions of the model include:

- Out-of-balance forces are 1N horizontally (Z direction) and 1N vertically (Y direction) applied to the circular surface of the PU slide where it makes contact with the spindle.
- Constant Damping ratio is 0.01.
- The range of the excitation frequency is from 0 Hz (static) to 1 kHz.

The following results that have been generated using FEA show the performance of the structure after optimisation. First, Figure 7.20 below shows the dynamic response of the gantry in x, y and z directions. This result validates the design methodology as the structure that is most excited when it reaches 250 Hz, which is the fundamental natural frequency of the gantry as stated earlier in Table 6-1. Also, this value has been confirmed using the hammer test method after building the prototype. Overall, the maximum deformation of the gantry structure is below 1 micron, which indicates the design is capable of achieving a sub-micron machining accuracy when the previously mentioned optimisation method is applied.

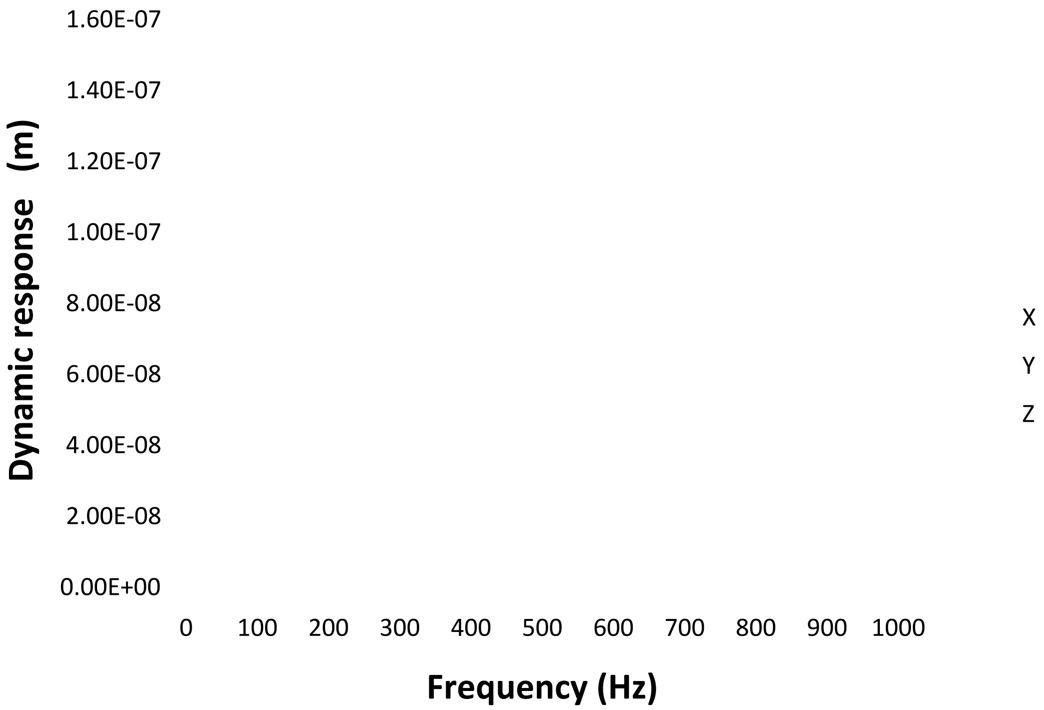


Figure 7.20: Dynamic response of the gantry structure in x,y and z directions.

The second result (Fig. 7.21) shows the reaction of the first part one of the hexagonal module. This part is most excited in the direction of z around 950 Hz, which also confirms the accuracy of the first model and hammer testing, as previously shown in Table 6-2 and Fig. 6.9. Compared to the measured deformation of the prototype at the same point, the current model is capable of minimising the value of deformation from 1.2 μm to less than 0.1 μm.

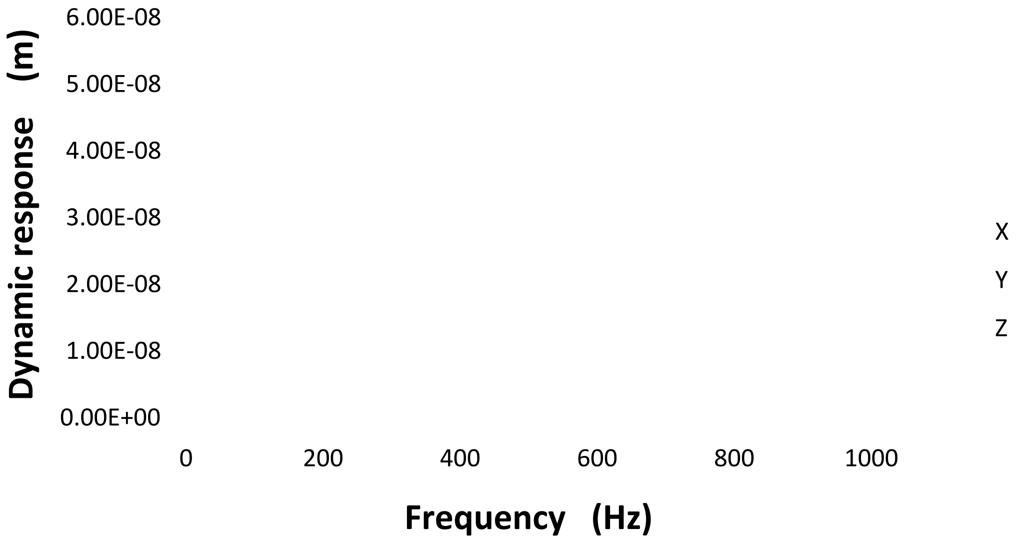


Figure 7.21: Dynamic response of part-1 of the hexagonal structure in three directions.

Finally, the second part of the hexagonal module shows a satisfactory performance, as it has a similar natural frequency range, yet it excites in all directions when approaching its fundamental natural frequency (Fig. 7.22).

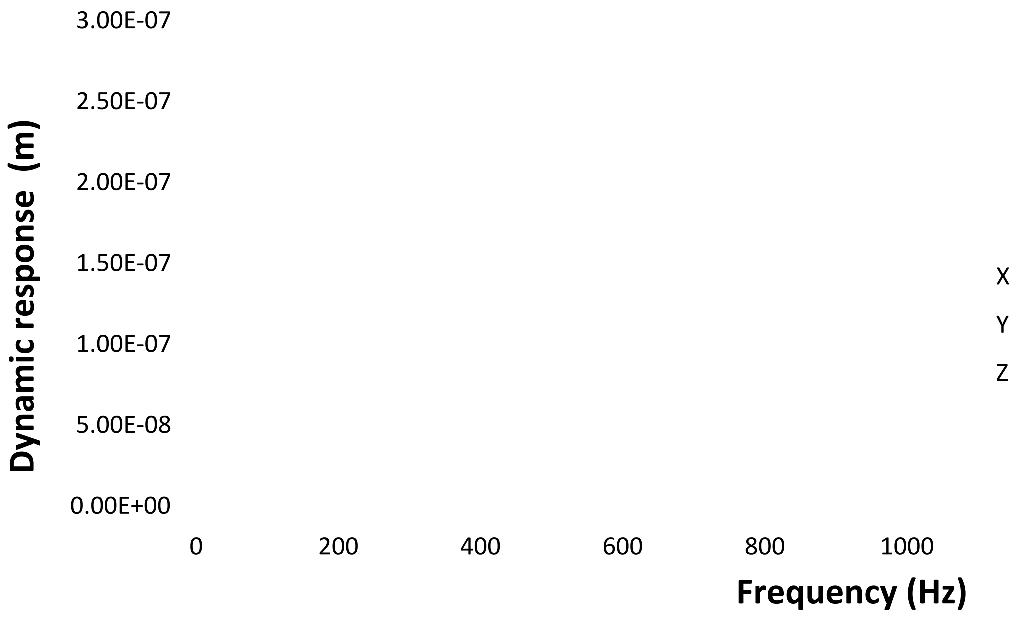


Figure 7.22: Dynamic response of the part-2 of the hexagonal structure in three directions.

In order to highlight the improvement in performance between the current design and the optimised model, a comparison based on the value of dynamic response has been carried out. Selecting dynamic response as a measure in this section was due to its direct involvement in the accuracy level of any machining process within the system, as it affects the position and performance of the tool tip, which leads to changes in machining aspects such as accuracy and surface finish quality. Based on this, reducing the dynamic response of the system is considered a significant target during this optimisation process.

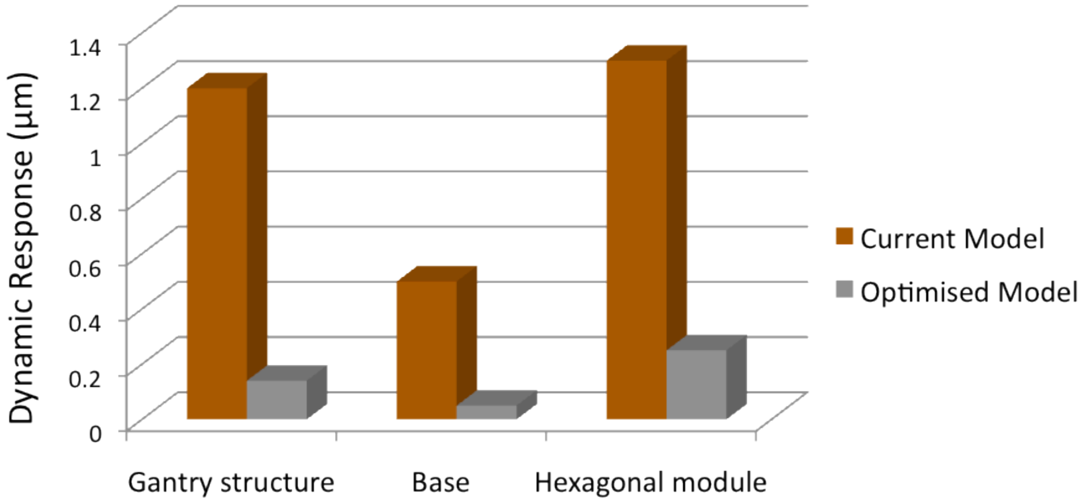


Figure 7.23: Dynamic response of the current and optimised model.

The results shown in (fig 7.23) indicate a significant improvement in performance within the system in three main positions (gantry structure, granite base and hexagonal module).

7.8 Summary

This chapter has described the optimisation methodology used to improve the performance of the RMC design in this research, starting with a review of the literature of some design optimisation methods with the aim of developing an understanding of this method. Following this, optimisation criteria have been set to achieve the aim of this process, focusing on three main design aspects: geometry, material and mechanical components. Each aspect has been analysed using scientific tools and methodologies in order to be optimised. Then, based on the results of this analysis, several recommendations have been made to improve performance. To validate this approach, a comparison between the current model and optimised model has been carried out and has confirmed that modifying each design aspect, as stated earlier, would improve the overall performance of the RMC.

Chapter 8:

Conclusions and Recommendations for Future Work

Chapter 8 - Conclusions and Recommendations for Future Work

8.1 Conclusions

In this research, a novel design for a Reconfigurable Micro-manufacturing Cell (RMC) has been developed with a focus on micro manufacturing. The introduction of such a design follows recent advances in miniature machine tool design and several aspects of today's manufacturing trends and technologies, such as strategies, market drivers and design methodologies. The novel design which has been described in this research provides a systematic approach on generating a valid machine design concept from scratch, highlighting five major steps, including reviewing the state of the art in micro factories, producing a novel conceptual design, building a prototype, testing and optimising the conceptual and physical models and finally providing a work conclusion summarising the entire experience, including a proposal for future work.

The first chapter is designed to state the main aim and a number of objectives of this research while addressing key research questions aimed at improving the state of the art as well as assessing the progress of each stage of the research. The following section (chapter 2) has provided an overview of four main areas of literature that have motivated the introduction of the design framework and methodology of this research. These four areas are micro manufacturing drivers and growth, manufacturing strategies, machine tool design and some of the recent advances in micro factory designs and solutions.

The framework that has been followed in order to deliver the novel design in chapter three consists of three main stages, each of which includes a design iteration loop. The aim of the first stage was to produce a conceptual design that progresses the state of the art. Also, design and modelling tools have been used during this stage as part of the design iteration to analyse and evaluate each design aspect before moving on to the second stage. These tools include design modelling and analysis software such as ANSYS, LabVIEW and ProEngineer. As a result, five design iterations have been developed and analysed before introducing a conceptual design that is capable of

delivering the required qualitative aspects, such as modularity and reconfigurability, while maintaining a high level of operational performance.
Based on developing a detailed conceptual design from stage one, building a physical model has been considered the second stage of this research. This process has included the fabrication, assembly and testing of the RMC, using limited resources including budget and timeframe. Moreover, key tasks have been considered during this stage, including developing a valid correlation between the design and the prototype, as well as maintaining a satisfactory level of operational performance. This task has been done by applying a number of design and modelling optimisation steps in order to achieve a high level of correlation between the conceptual model and the prototype using a fundamental natural frequency of each part of the structure as a comparison parameter. The resulting correlation values (up to 98%) meant that further modifications in the conceptual model could be achieved by the prototype, which opens the door for a new section to optimise the performance of the current RMC design.

Once all these tasks were satisfied, a design optimisation process was carried out, aimed at improving the performance of the current design and verifying its upgradability and reconfigurability. By performing several design optimisation assessments, the performance and productivity levels of the novel design have been verified, with indication of potential room for improvement, which can be achieved by applying the changes mentioned in the previous chapter. The optimisation process in this section has been based on applying modifications to a number of areas including the machine's geometry, selected material and mechanical components. Each area has been assessed based on comparing the performance with the current model. For example, the machine's geometry has been assessed based on comparing the static and dynamic deflection between the optimised model and the current model, as well as in comparing the selected material of the structure. Finally, an optimised model has been developed based on applying changes on these three areas, and this model has shown a better improvement in performance compared to the current model.

Overall, the previously mentioned development methodology and framework to design and assess the RMC in this research have generated several contributions to the field of micro manufacturing machine design. However, it has also identified some areas where this process can be optimised to become more productive and utilised further in the future.

8.2 Contributions to knowledge

This research has resulted in a number of contributions to knowledge based on satisfying the aim and objectives of the research, as well as answering the previously mentioned research questions. These contributions include:

* The introduction of a novel design for a reconfigurable micromachining cell (RMC), which has been based on combining features from a number of manufacturing strategies as well as presenting a radical new machine design. The proposed RMC in this research shows the effect of a selection of manufacturing strategies on the design of the RMC, which can be changed according to future demand. This novel design delivers the machining capabilities of conventional machine tools in a compact and significantly smaller footprint design that is modular and can be reconfigured rapidly to perform a wide range of machining processes on parts with an overall volume of (100 mm^3).

* The development of a conceptual design assessment and modelling methodology has been proposed and demonstrated in this research in order to improve the novel design and optimise it in the future. This methodology is considered a key element in upgrading the current design to cope with future market demands, as changes in demand will only require appliance of modifications to the methodology.

* A systematic design optimisation methodology has been developed and demonstrated to provide design optimisation and upgradability, as well as developing a link between the state of the art and even more commercial applications based on pre-set requirements and standards.

8.3 Recommendations for future work

Since this research involved developing several methodologies to produce and assess the design, several areas can be investigated further with the aim of promoting the current state of the art to be made available on a commercial level. This process can be initiated by performing a detailed investigation on areas of application, as each field requires a unique set of machine specifications and requirements. Following this, a detailed design methodology can be developed for each field based on the stated requirements.

Moreover, a link should be developed between the future demands of the market and the design methodology. The introduction of the framework in chapter three needs to be further developed, as currently it only covers a small area that concerns performance assessment based on a small number of qualitative criteria and a finite element analysis and modelling. Suggested expansion elements could involve environmental, financial and legislatorial aspects in order to provide any proposed design with more credibility and increase its chance of being produced on a commercial level.

Another potential area for future work involves optimisation methodology, where the introduction of "Topology Optimisation" software could be implemented in order to develop a novel design of RMC from scratch. This approach would help in developing a detailed design of the RMC – based on pre-set criteria – without the need to go through various design iterations, providing the advantage of saving time and effort as it minimises the required time-to-market (TTM). Furthermore, this approach would make the optimisation process more applicable to real-world design problems by extending it to include more modelling methods and optimisation algorithms in order to build codes and incorporate material databases.

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Appendices

Appendix I

Academic Publications

Publication Arising from This Research

1. Alsharif, R., Makatsoris, C., Sadik, S., 2008. "A Novel Architecture for a Re-configurable Micro Machining Cell", The 6th International Conference on Manufacturing Research Proceedings, Brunel University, UK, September 9-11, 2008, pp. 437-445.

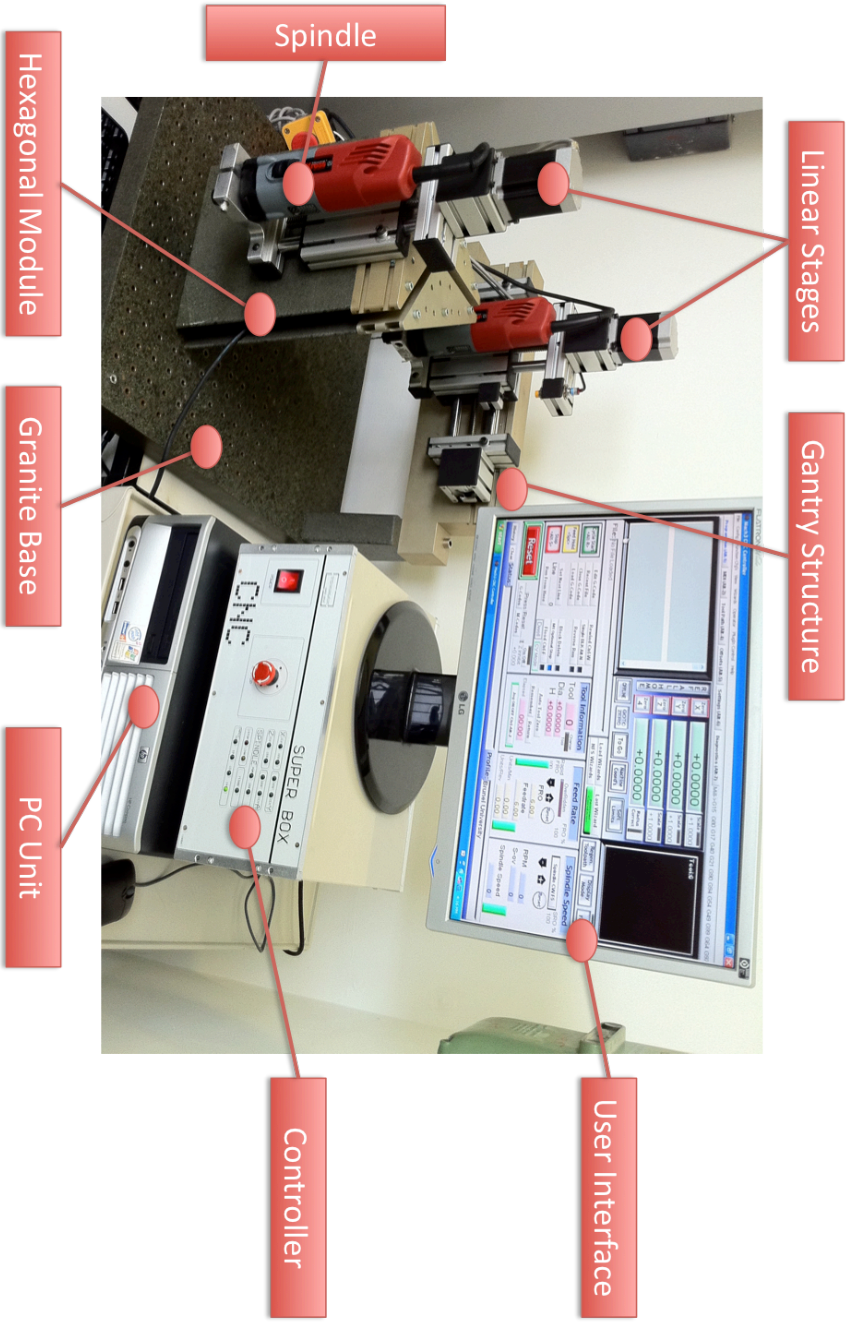
2. Alsharif, R., Makatsoris, C., 2009. "Design of a Novel, Composite and Reconfigurable MicroManufacturing Machine". Lamdamap 9th International Conference, 30th June – 2nd July 2009.

3. Alsharif, R., Makatsoris, C., 2011."Reconfigurable Micromachining Cell (RMC): A Novel Design". MM Live UK 2011 Micro Manufacturing Conference, 27-29 September 2011, NEC, Birmingham, UK (accepted).

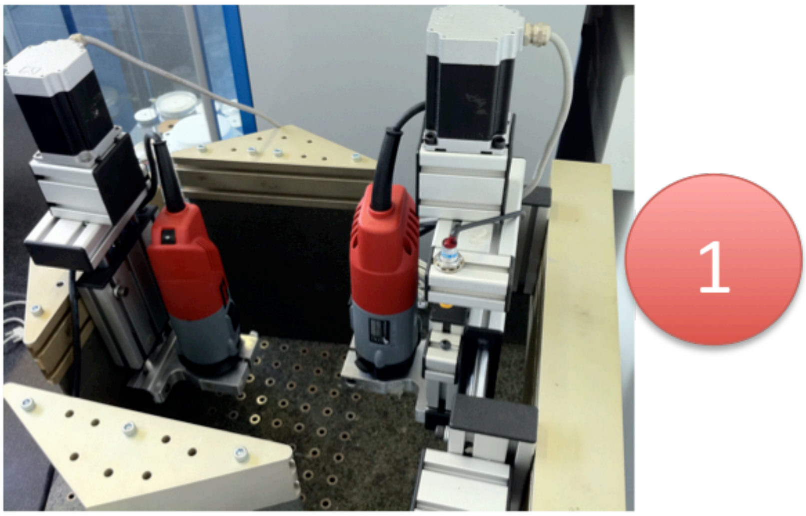
Appendix II:

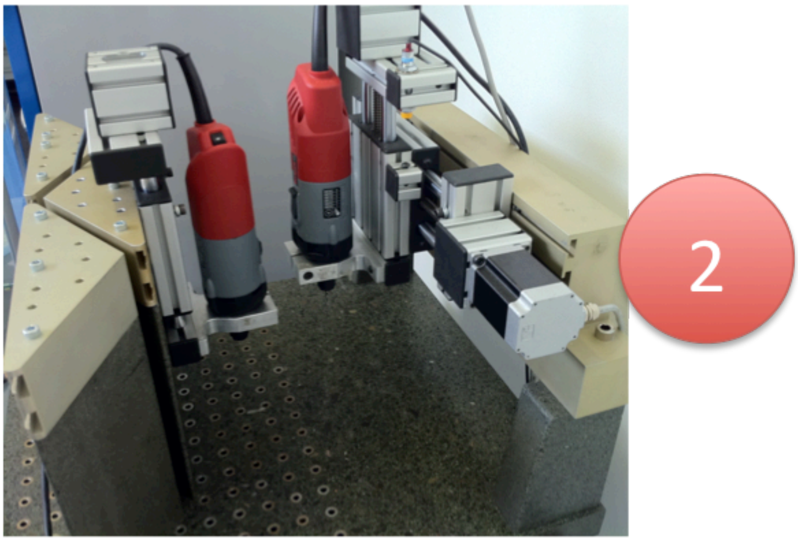
RMC Prototype

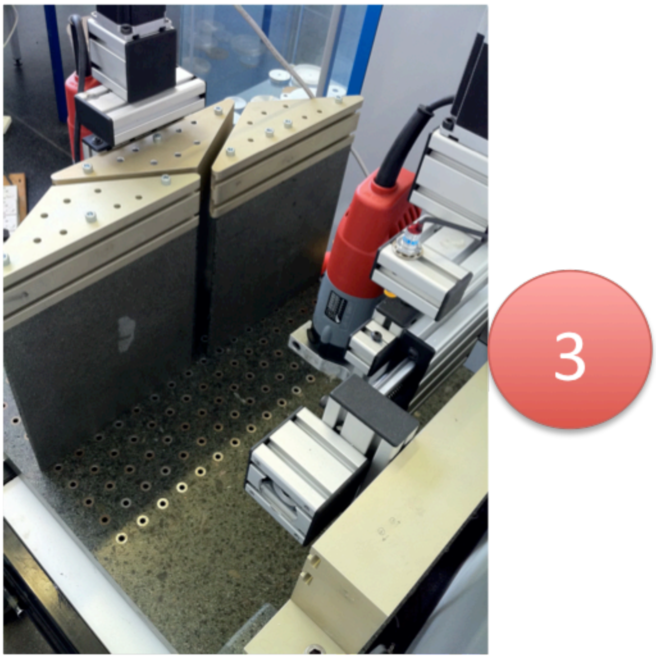
- Fully assembled RMC prototype

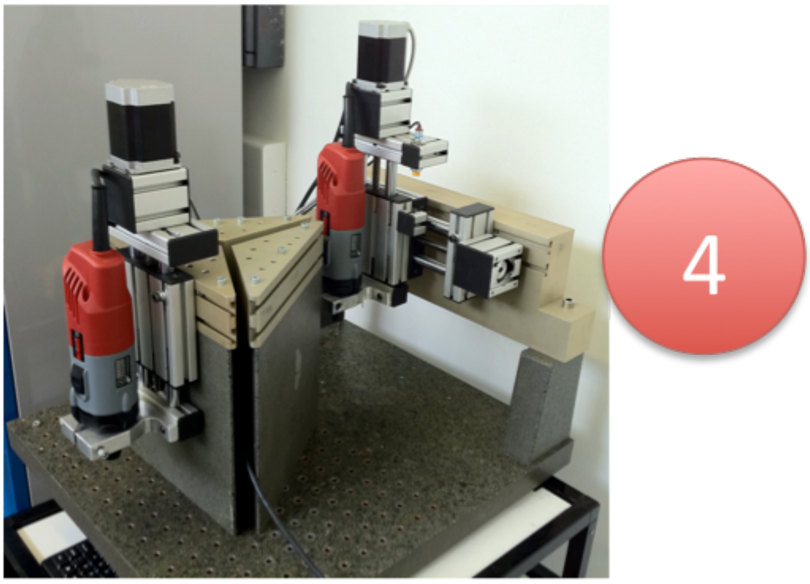


Several configurations of the RMC;

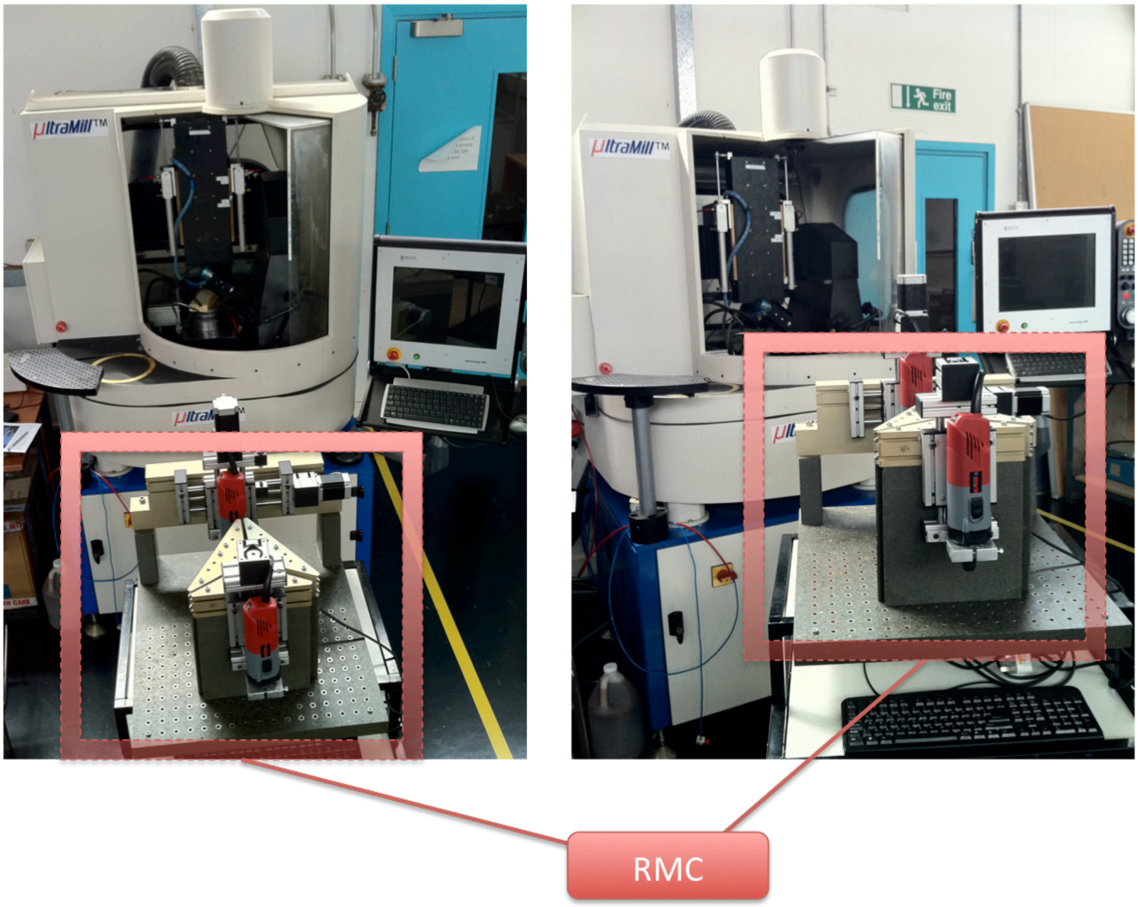








- RMC Prototype compared to Brunel University's 5-Axis UltraMill

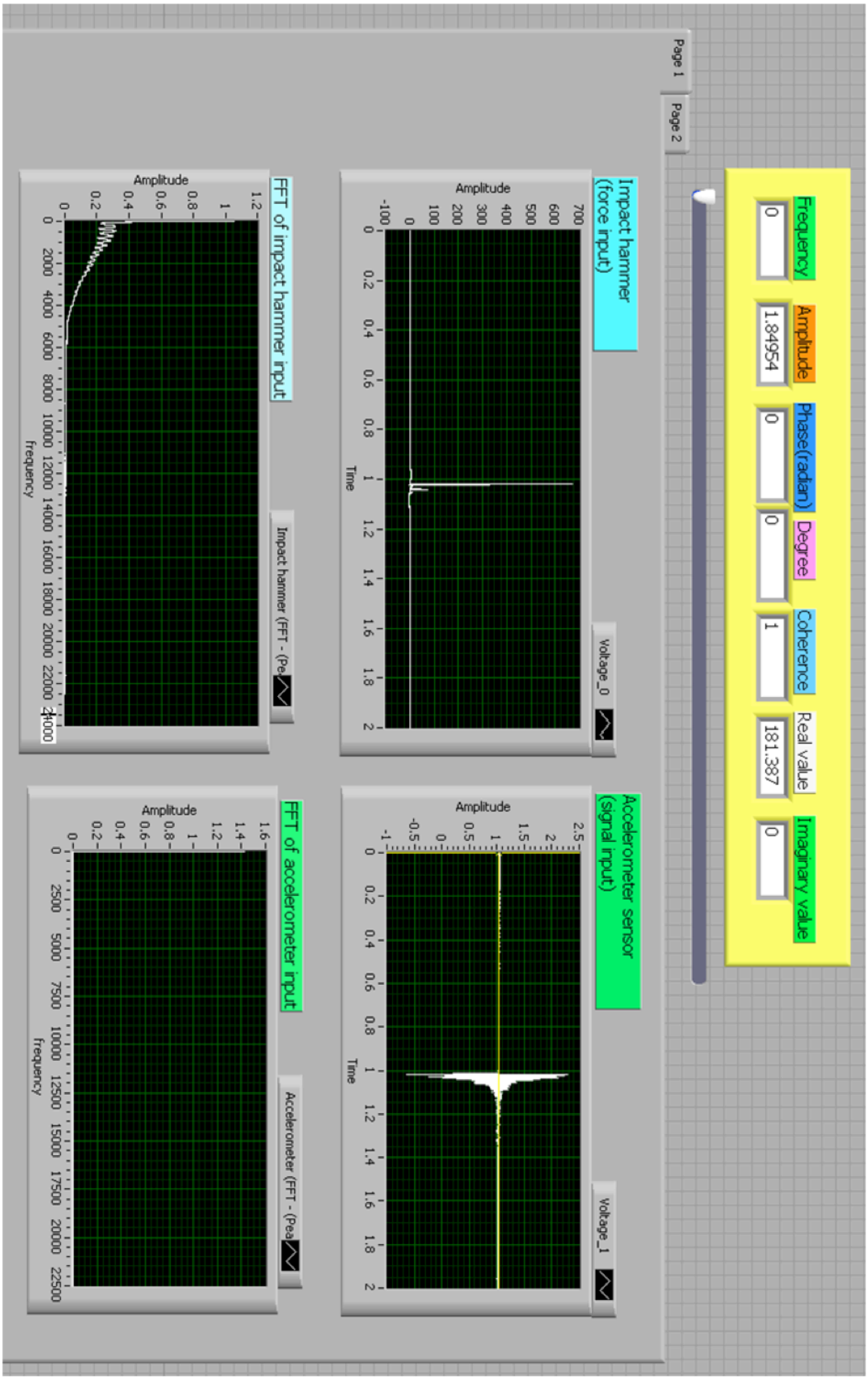


Appendix III:

Part of LabVIEW Programming

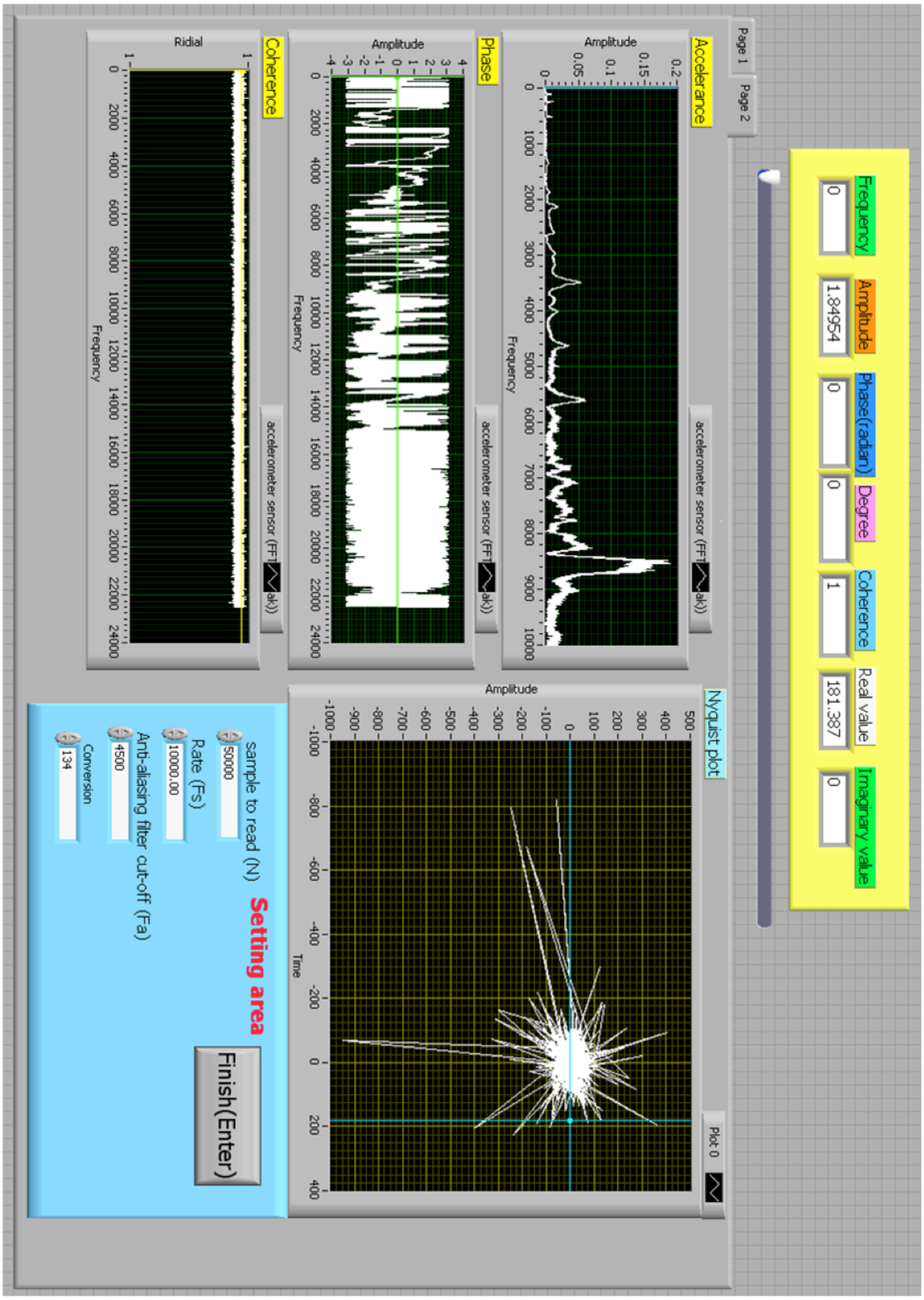
Part of LabVIEW Programming:

Panel Screen Shot (1)



Part of LabVIEW Programming:

Panel Screen Shot (2)



Part of LabVIEW Programming:

Accelerometers (readings)

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3	0.002436	2.553235	1	0.004536	0.001082
4	0.000993	2.53989	1	0.002126	0.004734
5	0.001792	0.06305	1	0.001956	0.000985
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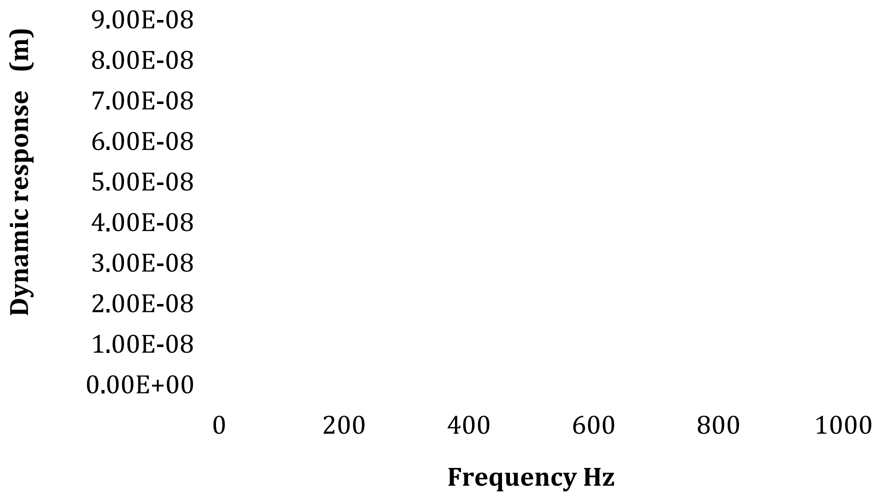
Appendix IV:

Part of ANSYS Programming

Part of ANSYS Programming:

Model Analysis (1)



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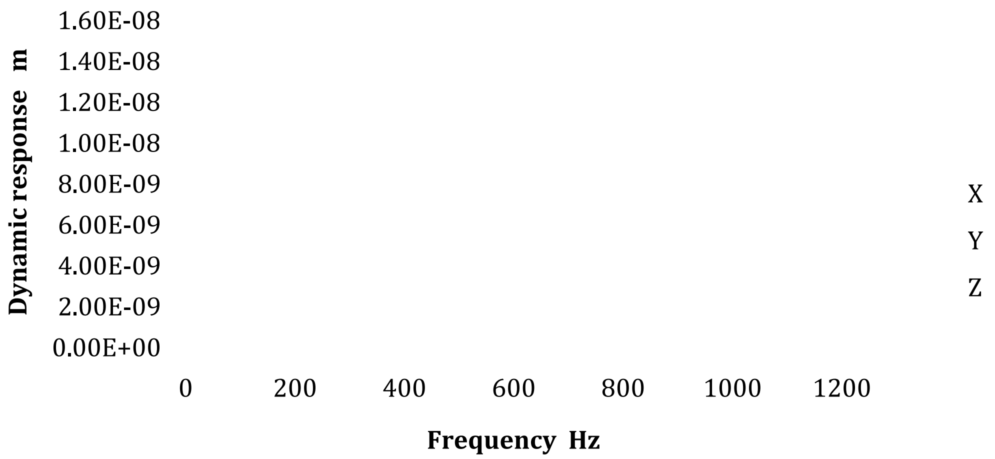
120	1.21E-10	3.82E-12	4.83E-11
140	1.39E-10	4.02E-12	4.93E-11
160	1.67E-10	4.32E-12	5.01E-11
180	2.13E-10	4.79E-12	5.03E-11
200	3.00E-10	5.64E-12	4.87E-11
220	5.18E-10	7.74E-12	3.95E-11
240	2.02E-09	2.20E-11	5.03E-11
260	1.03E-09	6.79E-12	1.51E-10
280	4.08E-10	8.34E-13	1.20E-10
300	2.51E-10	6.87E-13	1.21E-10
320	1.78E-10	1.41E-12	1.30E-10
340	1.34E-10	1.85E-12	1.47E-10
360	1.00E-10	2.16E-12	1.72E-10
380	6.83E-11	2.42E-12	2.12E-10
400	2.35E-11	2.80E-12	2.86E-10
420	1.27E-10	6.04E-12	5.38E-10
440	7.00E-11	1.75E-11	4.28E-10
460	3.17E-10	1.93E-11	3.62E-10
480	1.56E-10	9.34E-12	9.93E-11
500	9.23E-11	8.08E-12	3.61E-10
520	1.67E-11	8.11E-12	9.51E-10
540	1.36E-08	3.72E-11	7.92E-08

560	3.78E-10	8.02E-12	1.33E-09
580	2.81E-10	8.97E-12	7.43E-10
600	2.55E-10	9.99E-12	5.55E-10
620	2.50E-10	1.13E-11	4.67E-10
640	2.54E-10	1.28E-11	4.23E-10
660	2.67E-10	1.49E-11	4.02E-10
680	2.87E-10	1.75E-11	3.99E-10
700	3.16E-10	2.11E-11	4.11E-10
720	3.57E-10	2.62E-11	4.40E-10
740	4.16E-10	3.35E-11	4.93E-10
760	5.03E-10	4.53E-11	5.86E-10
780	6.55E-10	6.77E-11	7.78E-10
800	7.97E-10	8.96E-11	8.90E-10
820	1.44E-09	2.06E-10	1.83E-09
840	1.40E-08	2.81E-09	2.21E-08
860	7.19E-10	3.10E-10	2.12E-09
880	2.80E-10	1.68E-10	9.46E-10
900	1.17E-09	1.30E-10	4.62E-10
920	4.56E-09	1.63E-10	8.53E-10
940	1.44E-09	4.68E-11	2.21E-09
960	1.57E-08	4.37E-10	1.33E-09
980	4.55E-09	1.86E-10	2.53E-10
1000	3.43E-09	1.79E-10	4.00E-10



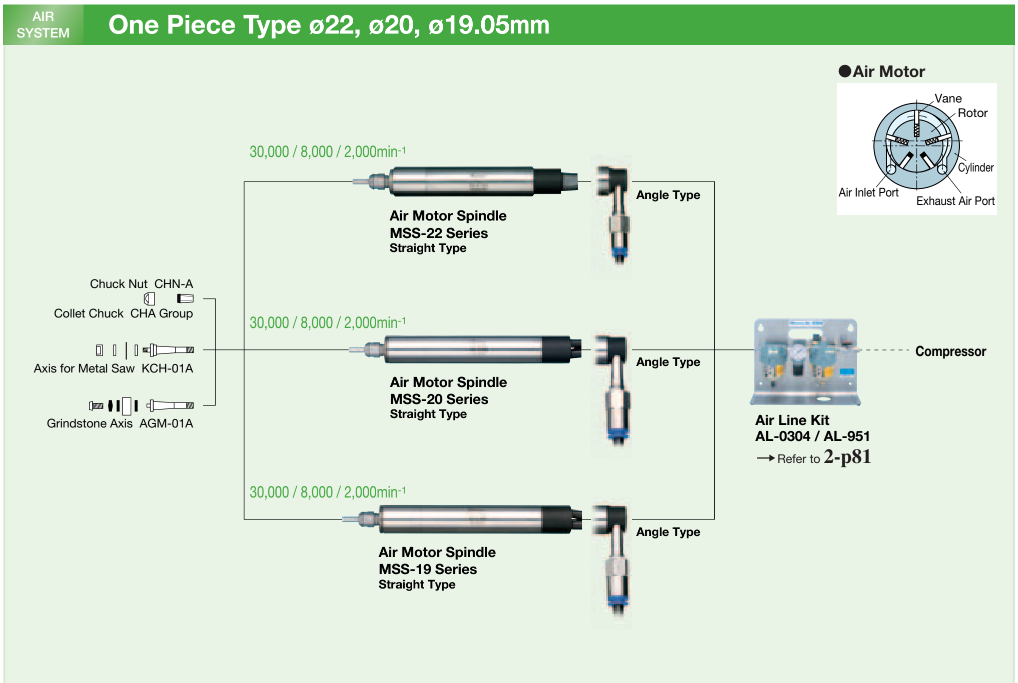
Hz	X	Y	Z
20	5.65E-11	6.68E-11	4.42E-11
40	5.78E-11	6.88E-11	4.44E-11
60	6.00E-11	7.23E-11	4.47E-11
80	6.34E-11	7.76E-11	4.50E-11
100	6.82E-11	8.52E-11	4.52E-11

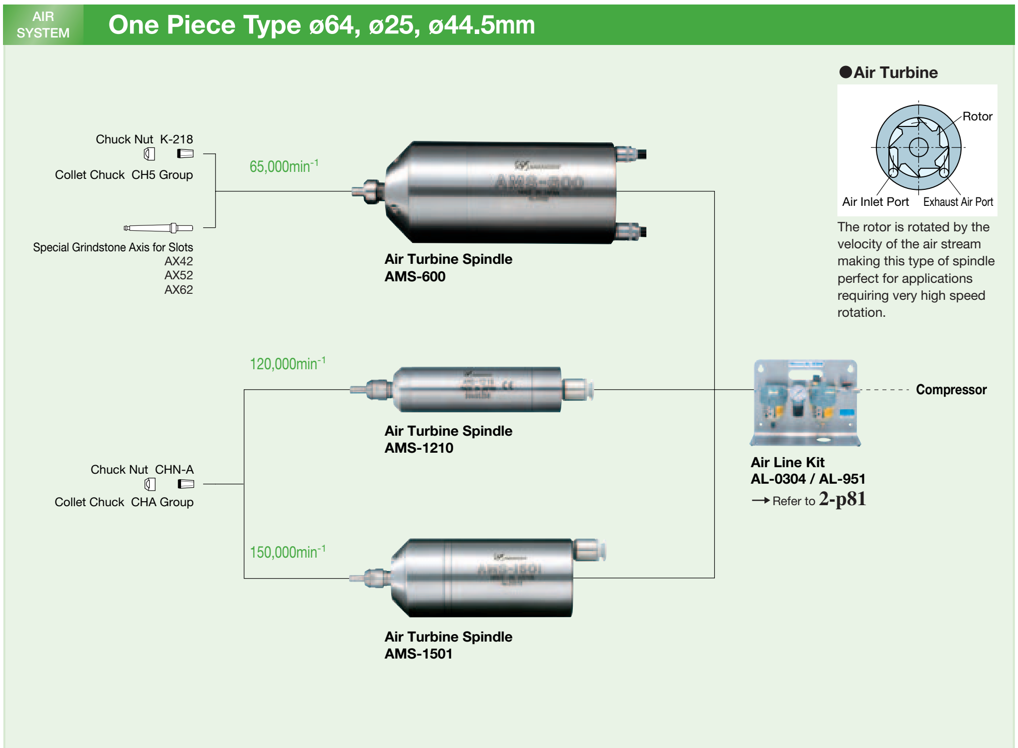
120	7.50E-11	9.63E-11	4.50E-11
140	8.47E-11	1.12E-10	4.39E-11
160	9.90E-11	1.37E-10	4.07E-11
180	1.22E-10	1.77E-10	3.27E-11
200	1.63E-10	2.52E-10	1.25E-11
220	2.61E-10	4.38E-10	5.44E-11
240	8.41E-10	1.59E-09	5.35E-10
260	4.13E-10	9.27E-10	5.68E-10
280	1.22E-10	3.69E-10	3.64E-10
300	3.67E-11	2.29E-10	3.46E-10
320	2.11E-11	1.63E-10	3.78E-10
340	7.48E-11	1.21E-10	4.47E-10
360	1.47E-10	8.61E-11	5.69E-10
380	2.67E-10	4.85E-11	7.89E-10
400	5.13E-10	2.01E-11	1.25E-09
420	1.29E-09	1.72E-10	2.73E-09
440	2.81E-09	5.84E-10	4.56E-09
460	4.87E-09	1.11E-09	7.14E-09
480	2.64E-09	6.12E-10	3.38E-09
500	2.67E-09	5.86E-10	2.94E-09
520	4.13E-09	8.10E-10	3.85E-09
540	1.41E-08	2.32E-09	1.09E-08
560	3.52E-09	4.43E-10	2.17E-09
580	1.73E-09	1.45E-10	8.12E-10
600	1.16E-09	4.65E-11	3.78E-10
620	8.99E-10	1.41E-11	1.71E-10
640	7.64E-10	4.03E-11	5.21E-11
660	6.95E-10	6.46E-11	5.57E-11
680	6.68E-10	8.67E-11	1.28E-10
700	6.74E-10	1.10E-10	2.03E-10
720	7.13E-10	1.37E-10	2.90E-10
740	7.90E-10	1.76E-10	4.06E-10
760	9.15E-10	2.49E-10	5.89E-10
780	1.09E-09	4.87E-10	9.72E-10
800	2.20E-09	5.81E-10	8.59E-10
820	3.76E-09	4.47E-10	1.86E-09
840	1.02E-08	1.66E-09	5.86E-09
860	4.43E-09	1.29E-09	2.77E-09
880	2.32E-09	1.29E-09	1.54E-09
900	1.52E-09	1.86E-09	1.13E-09
920	1.24E-09	3.99E-09	1.05E-09
940	1.86E-09	2.52E-09	1.62E-09
960	2.07E-09	3.73E-09	4.14E-09
980	1.96E-09	2.12E-09	2.51E-09
1000	2.04E-09	1.57E-09	2.12E-09

Appendix V:

Mechanical Components – Data Sheet

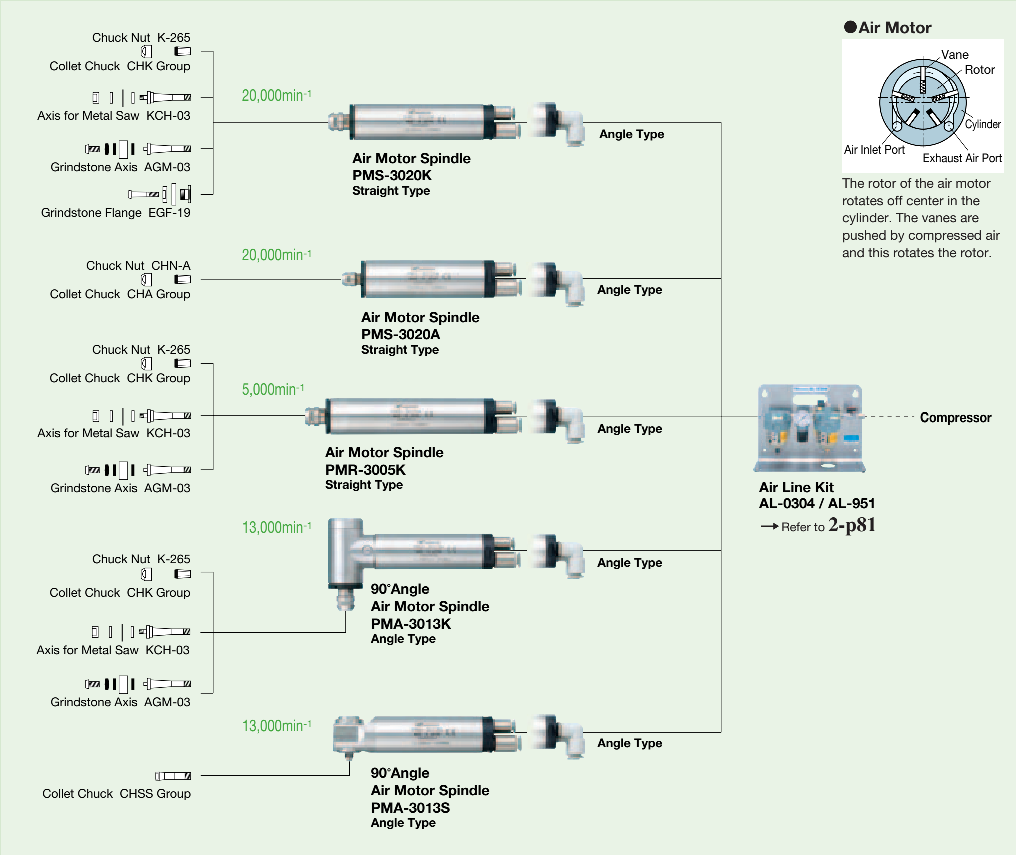
Specifications of new mechanical components





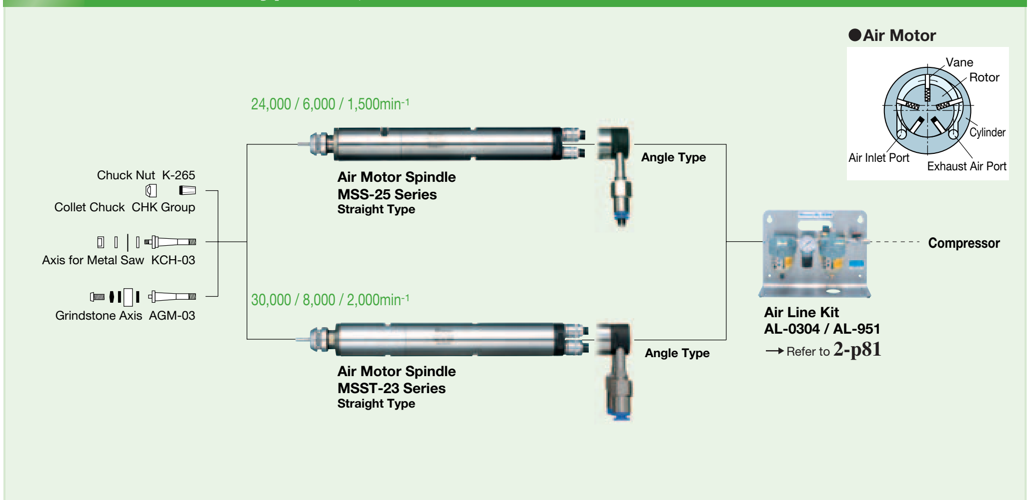
AIR SYSTEM

One Piece Type ø30mm



AIR SYSTEM

One Piece Type ø25, ø23mm



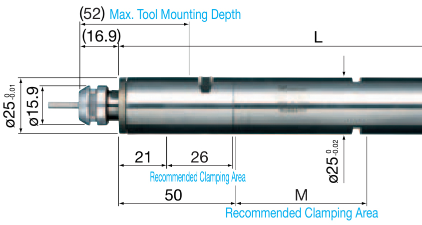
AIR SYSTEM

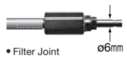
Air Motor Spindle

MSS-25 Series

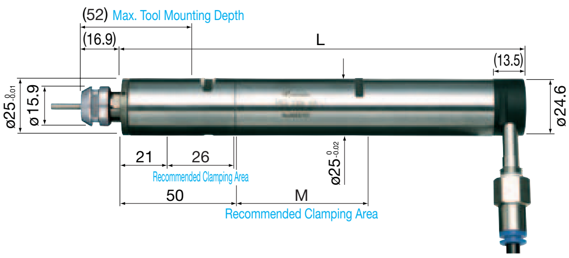
O.D.	Collet Chuck	Spindle Accuracy	Max. Output Power	Air Consumption
ø25mm	ø0.5~ø6.0mm (CHK Group)	Within 2 µm	130W	230NL/min

▼MSS-25 Series STRAIGHT TYPE (R)





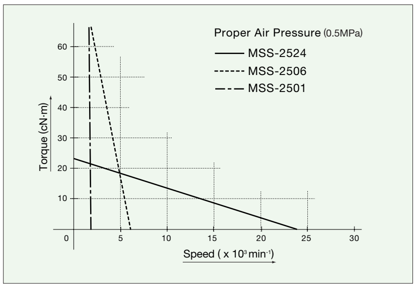
▼MSS-25 Series 90° ANGLE TYPE (RA)



< Specifications >

Proper Air Pressure		: 0.3~0.5MPa
Length of Motor Hose		: 2m
Hose Diameter (R-type)	Air Inlet	: ø6.7mm (O.D.)
	Exhaust Air	: ø7.5mm (O.D.)
Hose Diameter (RA-type)	Air Inlet	: ø6.0mm (O.D.)
	Exhaust Air	: ø8.0mm (O.D.)

● MSS-25 Series Torque-Speed Characteristics



⚠ Two recommended clamp areas are laser-marked on the spindle. Select one of them for clamping, and do not clamp both areas.

24,000min^{-1} (0.5MPa)

CAT. No.	Model	Shape	Max. Torque	Weight	L	M
1690	MSS-2524R	Straight	22.5cN·m	395g	131.3mm	25mm
1692	MSS-2524RA	90° Angle		436g	137.8mm	

6,000min^{-1} (0.5MPa) 1/4 Speed Reduction

CAT. No.	Model	Shape	Max. Torque	Weight	L	M
1698	MSS-2506R	Straight	85cN·m	485g	164.1mm	58mm
1700	MSS-2506RA	90° Angle		526g	170.6mm	

1,500min^{-1} (0.5MPa) 1/16 Speed Reduction

CAT. No.	Model	Shape	Max. Torque	Weight	L	M
1706	MSS-2501R	Straight	332cN·m	475g	168.5mm	62mm
1708	MSS-2501RA	90° Angle		516g	175.0mm	

▼ AIR MOTOR SPINDLE (One Piece Type)

MS Series

COOLANT

Outside Diameter ø25, ø23, ø22, ø20, ø19.05mm

Max. 30,000min^{-1}

Max. Output Power 130W

Model Code Example	
[1] SERIES CODE [2] OUTSIDE DIAMETER [3] SPEED [4] R=FORWARD (Right) [5] CODE FOR 90° ANGLE TYPE	• Straight Type MSS [1] 19 [2] 08 [3] R [4] • 90° Angle Type MSS [1] 19 [2] 08 [3] R [4] A [5]

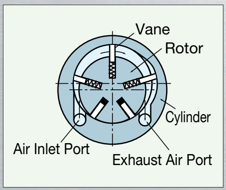
Spindle Accuracy : Within 2 µm

Outer Housing Material
Made from stainless steel (SUS416)

Configuration
2 Types available, Straight type & 90°Angle type.

The design of NAKANISHI's air motors and air turbines gives the highest output power is this small spindle class.

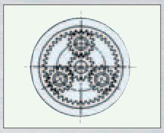
●Air Motor



The rotor of the air motor rotates off center in the cylinder. The vanes are pushed by compressed air and this rotates the rotor. This small air motor produces high torque making it suitable for small diameter drilling, milling, slitting and grinding.

Silencer
By utilizing a silencer on the exhaust air tubing the noise generated by the motor or turbine is greatly reduced.

Speed Reduction System
A planetary gear speed reduction system is in corporated in some of the MS Series motor/spindles. The speed reduction ratio is either 1/4 or 1/16.



1/4 · 1/16 : Planetary Gear System

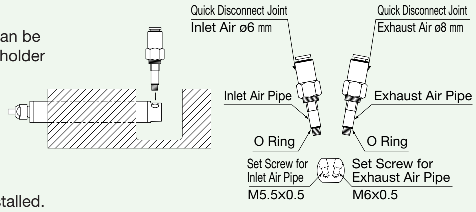
Air Line Kit
AL-0304

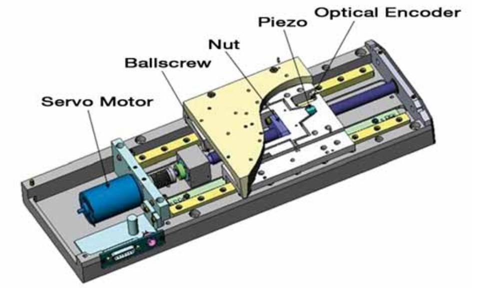
OPTION Refer to 2-p81

Installation of 90° Angle Type

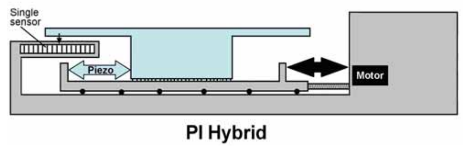
●MSS · MSST series angle (RA) type drive air and exhaust air pipes can be removed enabling the motor spindle installed through the front of a holder with backside restriction as shown in the illustration.

Installation
[1] Remove Inlet and Exhaust Air Pipes from motor spindle.
[2] Insert the straight spindle from the front side of holder and fix it.
[3] Mount the inlet and exhaust air pipes to the spindle fixed on the holder and attach a hose to the quick disconnect joint.
• Urethane hose of 6 x 4 for inlet air and 8 x 5 for exhaust air can be installed.





Working principle of the M-511.HD. The platform is decoupled from the motor drive train by the piezo actuator and the flexure guides. This also reduces the inertia of the piezo-driven platform and allows for rapid response



PI Hybrid drive combines motorized and piezo positioning system with integrated, internal, high-resolution sensor in one control loop

Technical Data

Model	M-511.HD
Active axes	X
Motion and positioning	
Travel range	100 mm
Integrated sensor	Linear encoder
Sensor resolution	0.002 µm
Design resolution	0.002 µm
Min. incremental motion	0.004 µm
Hysteresis at the platform	0.01 µm
Unidirectional repeatability	0.01 µm
Accuracy	<0.05 µm
Pitch	±25 µrad
Yaw	±25 µrad
Straightness	1 µm
Flatness	1 µm
Max. velocity	50 mm/s
Origin repeatability	1 µm
Mechanical properties	
Drive screw	Recirculating ballscrews
Guiding	Precision linear guiding rails, recirculating ball bearings
Screw pitch	2 mm/rev.
Max. load	200 N
Max. push/pull force	80/80 N
Max. lateral force	200 N
Drive properties	
Drive type	Hybrid drive: DC motor with low-inertia, flexure-decoupled and piezo actuated stage platform
Motor type	DC motor
Operating voltage (motor)	24 V
Electrical power	30 W
Piezo drive type	PICMA® Multilayer piezo with flexure
Piezo voltage	±36 V
Limit and reference switches	Hall-effect
Miscellaneous	
Operating temperature range	-20 to +65 °C
Material	Al (black anodized)
Mass	5.1 kg
Recommended controller/driver	C-702 hybrid motor controller (p. 4-118)

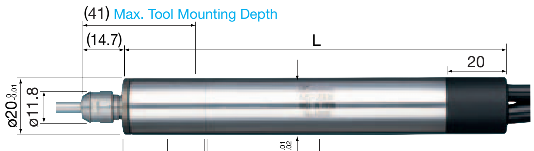
AIR SYSTEM

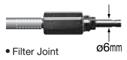
Air Motor Spindle

MSS-20 Series

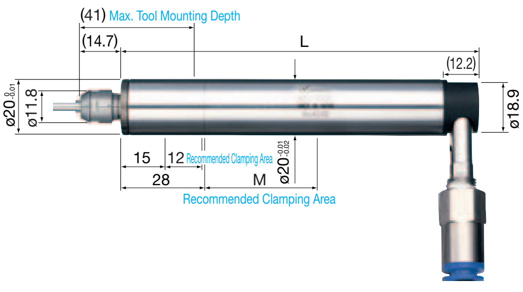
O.D.	Collet Chuck	Spindle Accuracy	Max. Output Power	Air Consumption
ø20mm	ø0.5~ø4.0mm (CHA Group)	Within 2 μm	63W	130NL/min

MSS-20 Series STRAIGHT TYPE (R)





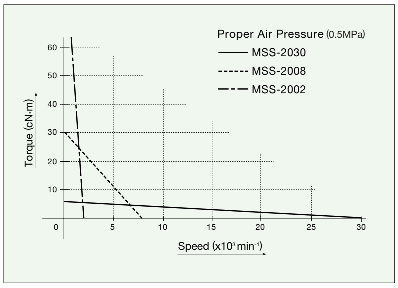
MSS-20 Series 90° ANGLE TYPE (RA)



< Specifications >

Proper Air Pressure		: 0.3~0.5MPa
Length of Motor Hose		: 2m
Hose Diameter (R-type)	Air Inlet	: ø5.7mm (O.D.)
	Exhaust Air	: ø6.5mm (O.D.)
Hose Diameter (RA-type)	Air Inlet	: ø6.0mm (O.D.)
	Exhaust Air	: ø8.0mm (O.D.)

● MSS-20 Series Torque-Speed Characteristics



Two recommended clamp areas are laser-marked on the spindle. Select one of them for clamping, and do not clamp both areas.

30,000 min⁻¹ (0.5MPa)

CAT. No.		Model		Shape		Max. Torque		Weight		L		M	
CAT. No.	1710	Model	MSS-2030R	Shape	Straight	Max. Torque	7.8cN·m	Weight	190g	L	110.9mm	M	23mm
CAT. No.	1712	Model	MSS-2030RA	Shape	90° Angle			Weight	239g	L	103.1mm		

8,000 min⁻¹ (0.5MPa) 1/4 Speed Reduction

CAT. No.		Model		Shape		Max. Torque		Weight		L		M	
CAT. No.	1609	Model	MSS-2008R	Shape	Straight	Max. Torque	30.4cN·m	Weight	225g	L	126.8mm	M	39mm
CAT. No.	1611	Model	MSS-2008RA	Shape	90° Angle			Weight	274g	L	119.0mm		

2,000 min⁻¹ (0.5MPa) 1/16 Speed Reduction

CAT. No.		Model		Shape		Max. Torque		Weight		L		M	
CAT. No.	1613	Model	MSS-2002R	Shape	Straight	Max. Torque	120cN·m	Weight	241g	L	141.0mm	M	53mm
CAT. No.	1615	Model	MSS-2002RA	Shape	90° Angle			Weight	290g	L	133.2mm		

< Standard Equipment · Accessories >

- Collet Chuck ø3.0mm (CHA-3.0) • Chuck Nut (CHN-A)
- Spanner (8 x 5), (9 x 11) : 1pc. each
- Hose (K-221) (R-type) : 2m
- Hose (K-215) (RA-type) : ø6mm x 2m
- Hose (K-216) (RA-type) : ø8mm x 1m
- Silencer (K-209) (R-type) • Silencer (K-208) (RA-type)

< Optional >

Collet Chuck (CHA Group)	: ø0.5~ø4.0mm See Page 7-p2 for details
Metal Saw Axis (KCH-01A)	: For ø6.0 (I.D.) x ø30mm (O.D.)
Grindstone Axis (AGM-01A)	: For grinding wheel with I.D. of ø5.0mm