ΕΛΛΗΝΙΚΗ ΔΗΜΟΚΡΑΤΙΑ
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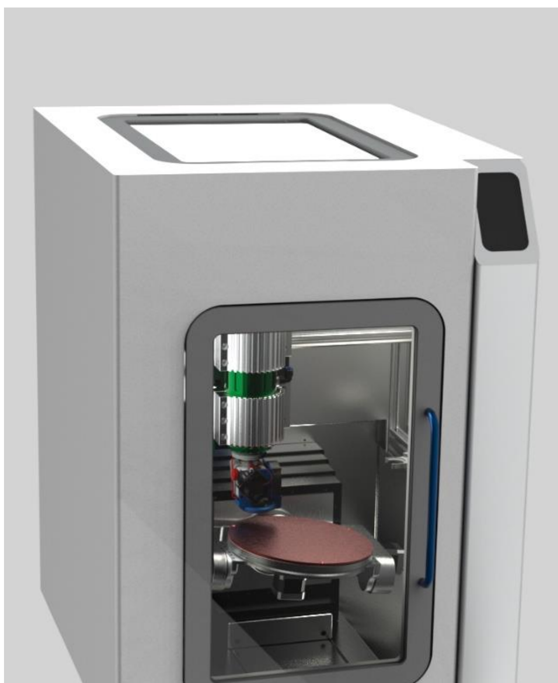
ΣΥΓΚΡΟΤΗΜΑ ΕΥΡΙΠΟΥ – ΓΕΝΙΚΟ ΤΜΗΜΑ

ΠΡΟΓΡΑΜΜΑ ΜΕΤΑΠΤΥΧΙΑΚΩΝ ΣΠΟΥΔΩΝ

"Σχεδίαση και Κατασκευή Συστημάτων Αγωνιστικών Οχημάτων"
"MSc Design and Manufacturing of Sports Vehicle Systems"

Διπλωματική Εργασία

"Σχεδιασμός και ανάλυση συστημάτων υβριδικού 5-αξονικού κέντρου κατεργασίας και 3-αξονικού 3Δ εκτυπωτή για την κατασκευή πλαστικών τεμαχίων"



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ΨΑΧΝΑ, 2022

ΕΘΝΙΚΟ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ
ΓΕΝΙΚΟ ΤΜΗΜΑ

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« ΣΧΕΔΙΑΣΗ ΚΑΙ ΚΑΤΑΣΚΕΥΗ ΣΥΣΤΗΜΑΤΩΝ ΑΓΩΝΙΣΤΙΚΩΝ ΟΧΗΜΑΤΩΝ »

Δήλωση Αυθεντικότητας, ζητήματα αντιγραφής και χρήσης

Η παρούσα εργασία αποτελεί πνευματική ιδιοκτησία του σπουδαστή Ιορδανίδη Μ. Δημητρίου που την εκπόνησε. Στο πλαίσιο της πολιτικής ανοικτής πρόσβασης ο συγγραφέας – δημιουργός εκχωρεί στο Εθνικόν και Καποδιστριακόν Πανεπιστήμιο Αθηνών, μη αποκλειστική άδεια χρήσης του δικαιώματος αναπαραγωγής, προσαρμογής δημοσίου δανεισμού, παρουσίασης στο κοινό και ψηφιακής διάχυσης τους διεθνώς, σε ηλεκτρονική μορφή και σε οποιοδήποτε μέσο, για διδακτικούς και ερευνητικούς σκοπούς, άνευ ανταλλάγματος και για όλο το χρόνο διάρκειας των δικαιωμάτων πνευματικής ιδιοκτησίας.

Η ανοικτή πρόσβαση στο πλήρες κείμενο για μελέτη και ανάγνωση δεν σημαίνει καθ' οποιονδήποτε τρόπο παραχώρηση δικαιωμάτων διανοητικής ιδιοκτησίας του συγγραφέα/δημιουργού ούτε επιτρέπει την αναπαραγωγή, αναδημοσίευση, αντιγραφή, αποθήκευση, πώληση, εμπορική χρήση, μετάδοση, διανομή, έκδοση, εκτέλεση, «μεταφόρτωση» (downloading), «ανάρτηση» (uploading), μετάφραση, τροποποίηση με οποιονδήποτε τρόπο, τμηματικά ή περιληπτικά της εργασίας, χωρίς τη ρητή προηγούμενη έγγραφη συναίνεση του συγγραφέα/δημιουργού. Ο συγγραφέας/ δημιουργός διατηρεί το σύνολο των ηθικών και περιουσιακών του δικαιωμάτων.

-Ο-

Ιορδανίδης Δημήτριος

ΨΑΧΝΑ, 2022

Διπλωματική Εργασία
του μεταπτυχιακού φοιτητή Ιορδανίδη Μ. Δημήτριου

«Σχεδιασμός και ανάλυση συστημάτων υβριδικού 5-αξονικου κέντρου κατεργασίας και 3-αξονίκου 3Δ εκτυπωτή για την κατασκευή πλαστικών τεμαχίων»

Η παρούσα Διπλωματική Εργασία εγκρίθηκε ομόφωνα από την τριμελή εξεταστική επιτροπή η οποία ορίστηκε από την Γενική Συνέλευση του Γενικού Τμήματος του Εθνικού και Καποδιστριακού Πανεπιστημίου Αθηνών, σύμφωνα με το νόμο και τον εγκεκριμένο οδηγό σπουδών του ΠΜΣ Σχεδίαση και Κατασκευή Συστημάτων Αγωνιστικών Οχημάτων. Τα μέλη της Επιτροπής ήταν ο κ. Αγαθοκλής Κριμπένης, ο κ. Στυλιανός Μαρκολέφας και ο κ. Αντώνιος Φατσής.

Εξεταστική Επιτροπή Διπλωματικής Εργασίας

(Υπογραφή)	*(Υπογραφή)*	*(Υπογραφή)*
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Αγαθοκλής Κριμπένης	Στυλιανός Μαρκολέφας	Αντώνιος Φατσής
Επίκ. Καθηγητής Ε.Κ.Π.Α.	Επίκ. Καθηγητής Ε.Κ.Π.Α.	Καθηγητής Ε.Κ.Π.Α.

ΨΑΧΝΑ, 2022

Ευχαριστίες

Σε αυτό το σημείο θα ήθελα να ευχαριστήσω όλους τους καθηγητές που βοήθησαν στην πνευματική και ηθική μου ανάπτυξη. Που αφιέρωσαν χρόνο, κόπο και γνώσεις για να είμαι πλέον σε θέση να παρουσιάσω και εγώ με τη σειρά μου, το έργο μου στην ανθρωπότητα.

Επίσης θα ήθελα να δώσω τις ιδιαίτερες ευχαριστίες μου σε συγκεκριμένους ανθρώπους, οι οποίοι με βοήθησαν στην ολοκλήρωση αυτής της μελέτης.

Πιο συγκεκριμένα:

- Δρ. Μηχ. Α. Κριμπένης, Επίκουρος Καθηγητής, Επιβλέπων καθηγητής της μελέτης αυτής. Εμπνευστής και μέντοράς μου.

Περίληψη

Σκοπός της παρούσας διπλωματικής εργασίας είναι η μελέτη σχεδίασης μια υβριδικής ψηφιακά καθοδηγούμενης εργαλειομηχανής, η οποία συνδυάζει της λειτουργία ενός 5-αξονικού κέντρου κατεργασίας CNC με ένα 5-αξονικόυ τρισδιάστατου εκτυπωτή, που ως στόχο έχει τη κατασκευή τεμαχίων από πολυμερή, ελαστομέρη και ειδικού τύπου σύνθετα υλικά (πχ. ενισχυμένο νήμα με ίνες άνθρακα) ειδικής πολυπλοκότητας, τα οποία απαιτούν την ελάχιστη μετέπειτα επεξεργασία για να προκύψει τελικό προϊόν στο ελάχιστο δυνατό χρόνο. Για την επιβεβαίωση και ολοκλήρωση της μελάτης σχεδίασης, υλοποιείται στατική και δυναμική ανάλυση με την μέθοδο των πεπερασμένων στοιχείων για την βελτίωση των σχεδιαστικών χαρακτηριστικών της δομής της εργαλειομηχανής. Επίσης, κατά τη μελέτη σχεδίασης αναπτύσσεται ένα καινοτόμο σύστημα για την αυτόματη αλλαγή κεφαλών τρισδιάστατων εκτυπωτών. Ο μηχανισμός αυτός επιτρέπει την προσαρμογή διαφόρων τύπων εξωθητήρων τρισδιάστατών εκτυπωτών σε τυποποιημένους κώνους εργαλείων CNC (πχ. SK16, BT40). Καινοτομία αποτελεί το γεγονός ότι για την μεταφορά ηλεκτρικής ενεργείας (παροχή) στην κεφαλή εκτύπωσης (extruder, hotend, κλπ) δεν χρησιμοποιούνται καλώδια και συνδέσεις, αλλά ειδικοί δακτύλιοι ολίσθησης. Με αυτόν το τρόπο επιτυγχάνονται πλήρως αυτοματοποιημένες αλλαγές εργαλείων σε μία υβριδική ψηφιακά καθοδηγούμενη εργαλειομηχανή.

Η έρευνα που διεξάχθηκε στα παραπάνω θέματα κατά τη διάρκεια της παρούσας διπλωματικής εργασίας παρουσιάζεται με τη μορφή δύο πρωτότυπων ερευνητικών άρθρων, τα οποία έχουν υποβληθεί προς δημοσίευση σε διεθνή επιστημονικά περιοδικά, με τίτλους:

1. Design and analysis of a desktop multi-axis hybrid milling-filament extrusion CNC machine tool for non-metallic materials
2. Material extrusion 3D printing system for hybrid CNC machines with automatically changed standard tool holders

Λέξεις – Κλειδιά: Τρισδιάστατη εκτύπωση, υβριδική ψηφιακά καθοδηγούμενη , πρόσθεση και αφαίρεση υλικού, υβριδική τεχνολογία, εξώθηση υλικού, αυτόματη αλλαγή εργαλείων

Abstract

The aim of this thesis it to study the design of a hybrid Computerized Numerical Control machine tool, which combines the operation of a 5-axis CNC machining center with a 5-axis 3D printer, which aims at producing polymer, elastomer and special material parts (eg. carbon fiber reinforced polymers) of special complexity, which require minimal subsequent post-processing to obtain the final product in the shortest possible time. To complement the above, static and dynamic analysis is achieved with the Finite Element Method to improve the design features of the machine tool structure. Also, the development of an innovative system for the automatic tool change of 3D printer heads is achieved. This mechanism allows various types of 3D printer extruders to be delivered to standard CNC tool cones (eg SK16, BT40). Innovation lies in the fact that for the transfer of electricity to the print head (extruder, hotend, etc) no cables and connections were used, but special design slip rings. This achieves fully automated tool changes on a hybrid numerically controlled machine tool.

Research that was conducted on the above, is presented in two scientific articles, which have been submitted for publication in international scientific journals:

1. Design and analysis of a desktop multi-axis hybrid milling-filament extrusion CNC machine tool for non-metallic materials
2. Material extrusion 3D printing system for hybrid CNC machines with automatically changed standard tool holders

Keywords: 3D printing, hybrid computerized numerical control machine, additive and subtractive material, hybrid technology, material extrusion, automatic tool change.

Design and analysis of a desktop multi-axis hybrid milling-filament extrusion CNC machine tool for non-metallic materials

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Abstract

Additive Manufacturing has unlocked the ability to introduce new concepts for parts of very high complexity to the industrial landscape, which could not be manufactured with traditional manufacturing processes in a single or in a small number of steps. However, surface quality of 3D printed parts and process repeatability are low to medium, at least in an industrial context. This study proposes a new design of a fully automated multi-axis hybrid Additive and Subtractive Computerized Numerical Control machine tool for non-metallic parts, which can overcome the drawbacks of both Additive and Subtractive Numerical Manufacturing. It combines the operation a 5-axis CNC machining center with a 5-axis extrusion 3D printer with automated tool head change, which is able to make parts made of polymer and special 3D printing materials (eg. carbon fiber reinforced filaments) of high complexity which require minimal post-processing to produce the final product in the shortest possible time. The design process also includes static, dynamic and harmonic response analysis with the Finite Elements Method, so as to improve design features of the machine tool structure. Results are presented and commented on in terms of machine efficiency to cope with applied loads during operation.

Keywords: 3D printing, CNC machining, additive and subtractive processes, finite element analysis, harmonic response analysis

1. Introduction

The need for time and cost savings plays a crucial role in the development of any industrial unit. In that direction, over the last two decades, the machine tool industry has started developing hybrid manufacturing machine tools. The term Hybrid Manufacturing (HM), and respectively Hybrid Machine Tools (HMT), refers to the combination of different manufacturing process in a single work environment, preferably enclosed or otherwise restricted ([1],[2],[3]). For the purposes of the present study, HMT are called the Computerized Numerical Control (CNC) machine tools, whose functions are controlled by a control unit or a computer, and they are combining material removal stages, known as Subtractive Manufacturing (SM), and material addition stages, commonly addressed as 3D printing or, more formally, Additive Manufacturing (AM) for the manufacture of components in a sequential or a parallel manner ([4],[5],[6]).

While most components can be made by either one of these two methods (SM or AM), modern manufacturing needs has driven machine tool manufacturers to evolve the existing machine tools, combining these machining methods in order to reduce production time, energy consumption, as well as material waste, with the ultimate goal of reducing total production cost per unit without sacrificing part quality. This is achieved by replacing the rough machining stage with material deposition, thus minimizing material usage and cutting tool wear, therefore cutting energy and cost. Besides, with the extended introduction of Topology Optimization and Generic Design techniques for component weight minimization, as in the ones for the aircraft, aerospace and transportation applications, the use of hybrid manufacturing methods is inevitably irreplaceable ([7],[4],[8]).

As with any mechanism with moving or rotating parts, vibrations are caused during the operation of the tools on a machine tool. These vibrations must be calculated and addressed properly ideally from the machine design stage, as they can cause deformations of the machine structure leading to part failure or even, in extreme case, to machine tool failure. Vibration can be described as a set of mode parameters, including natural frequency, operation pattern and damping. Natural frequency is an important component of the resonance effect. If the external excitation frequency is the same as that of the structure, it can cause permanent deformations ([9],[10]). In literature, three types of dynamic structural analysis techniques are known, (a) the distributed mass beam method, (b) the irradiated fixed beam method, and (c) the finite element method (FEM). FEM is one of the most useful tools for simulating physical models from very simple to very complex ones, and in most cases, such as the one analysed in this study, it is considered appropriate and efficient enough. Analyses' accuracy performed on CAE software depends mainly on the structure and the quality of the mesh. In this work, the dynamic characteristics of machine tools were studied using the FEM, as it incorporates material properties, geometric properties and boundary conditions were considered.

The aim of this study is to design a novel hybrid numerically controlled machine tool, which combines a 5-axis CNC machine center with a 5-axis 3D printer for the production of industrial grade high complexity parts made of polymers, elastomers and special type composites (eg. carbon fiber reinforced filament) that require minimal finishing by hand to obtain the final product in the shortest possible time. Static and dynamic analysis were iteratively used in the design process, thus providing knowledge in improving design features and predicting machine tool behavior under specific loads.

2. State of the art

Hybrid Manufacturing (HM) is an industry recognized term for combining at least two processing classes or at least two subcategories of the same processing class automatically without human intervention between processing phases. The prevailing term is 'hybrid manufacturing', as explained by Rajurkar et al. [11]. This description was somewhat vague due to the fact that the combination of two or more material removal processes is necessary in most machined parts. Kozak and Rajurkar [12] decided to adjust the definition, in the sense that performance characteristics of hybrid processing need to be significantly different than those of individual procedures when performed separately. In 2001, Aspinwall et al. [13] introduced the term "assisted machining" which defines HMT that combine two or more material removal processes, which are applied independently in the same machine, further reinforcing the definition of HM.

In the early 2010s [14], the realization that the term HM should be used in a broader sense to include processes other than machining led some authors to relate HM to any combination of processes, which involve various forms of deformation energy, that are used simultaneously in the same processing zone.

Fessler et al. [15] and Klocke and Wirtz [16] combined an older type of Laser Directed Energy Deposition (L-DED or, simpler, DED) system consisting of a laser with a coupled powder feed system (a device widely used for laser coating at the time) with a high-speed milling machine for performing material removal operations after intermediate metal deposition stages. Nevertheless, research about HM in the sense of alternating additive and material removal stages began to expand and consolidate only in the mid-2000s through the adaptation of either Metal Additive

Manufacturing (MAM) or material removal operations. Kerschbaumer and Ernst [17], for example, reviewed previous concepts and provided further insights into tool path generation, laser power source performance, and powder feed adaptation strategies. Sreenathbabu et al. [18] incorporated Gas Metal Arc Directed Energy Deposition (GMA-DED) into a CNC milling system for machining irregular layers in a more precise planar shape. Song et al. [19] assembled two Gas Metal Arc (GMA) lenses and a laser on a milling machine to obtain a hybrid multitasking system capable of providing a more accurate and selective metal deposition through an automated tool switching mechanism.

In the same line of hybrid multitasking systems, Kovacevic and Valant [20] patented a six-axis robotic system for the manufacture of metal components with plasma and laser-based deposition capabilities. Xinhong et al. [21] developed a system that combines the AM by Plasma Arc Direct Energy Deposition (PA-DED) and SM by milling to fabricate a built-in double air propeller made of a super nickel alloy.

The aforementioned and further test cases prompted the machine tool industry to develop and commercialize the first hybrid AM/SM systems in early 2010s. Thus, some of the traditional CNC manufacturers have introduced HMT models based on the DED technology for the AM operations. For example, DMG Mori introduced the LASERTEC 65 3D Hybrid model, Mazak the INTEGREX i-400AM, Okuma the MULTUS U laser EX model, Hermle the C-400 model and Optomec the CS series models among others. All these models offer multiple nozzle DED heads and multi-axis CNC machining, suitable for making from scratch or repairing (cladding) medium to large metallic parts made of Ti alloys and high performance steels with intricate geometries, such as impellers, gas and water turbine/compressor blades, jet engine nozzles etc. These systems are based on DED technology due to its greater flexibility to combine AM and SM in a single machine [22].

However, other CNC machine tool manufacturers focused on Powder Bed Fusion (PBF) technology for AM operations in their HMT, such as Matsuura with its Lumex Avance 25 and Sodick with its OPM250L and 350L models. These systems combine Laser Powder Bed Fusion (LPBF) deposition with high-speed milling and is gaining attention for its ability to perfect external contours, surface roughness and corrosion characteristics in dies and molds [23].

In order to create interchangeable AM heads that can fit in a typical CNC machine tool without serious intervention in its operations, a couple of companies developed stand-alone tool heads that can be fitted in the spindle with a simple tool change. Thus, 3d Hybrid offers GMA-DED, L-DED and cold spray heads (commonly used in coating applications) and Hybrid Manufacturing Technologies offers its AMBIT series for integration into CNC machining centers.

AM processes based on extrusion are among the most expensive and capable of producing surfaces with high accuracy. However, the use of this technology involves some manufacturing limitation such as the strength and size of the components due to long processing times. This can be eliminated by using the combinations of AM with SM. Due to the low cost of thermoplastic materials such as nylon and ABS, their use has become the only way to cost-effectively manufacture non-functional prototype parts. Fused Deposition Modeling (FDM) is one of the most common methods for manufacturing thermoplastics. In FDM material is extruded from drive wheels to a hot-end and then to the nozzle for subsequent deposition. Thermoplastic is deposited layer-by-layer to make complex components. Table 1 presents some of the hybrid systems that use thermoplastics.

5axismaker is a desktop machine tool that offers 5-axis milling and 3-axis printing. Creates components from wood, plastic, foam and other materials. Uses software to carve intricate products but only in three dimensions (X, Y and Z). Users must accurately rotate the object by hand or the lose the entire path. Additinally, use for dental applications [24].

Creality CP-01 is a modular machine with exchangeable head attachments for 3D printing, laser engraving and CNC engraving. For changing 3D printing, CNC cutting, Laser/CNC engraving the CP-01 has several head options with different tools, one for each of its functions. Each head has a universal connector to make any manual change easy, so reconfiguring the machine tool to switch between different functions regularly takes minutes. Materials that this machine is compatible with are PLA, ABS, and TRU. As a CNC machine, the CP-01 can sink its part into plastic, wood, paper and PCB [25][26].

The Snapmaker 2.0 is built for the lab and provides users with all the manufacturing capabilities that could potentially satisfy amateur applications. Users can swap out the unique 3D printing head for a CNC tool or laser diode. Since the Snapmaker has been referred to as a 3-in-1 build system, it includes a housing a rotary unit. The maximum temperature of the nozzle is 275^{o}C. Equipped with a direct drive extruder, this configuration will have no problems printing with materials such as PLA, ABS, PETG and TPU [27][28][29].

The ZMorph VX is a machine aimed at professionals and individuals looking for an affordable hybrid machine tool that combines 3D printing and CNC/laser machining for a variety of projects [30][31].

Table 1:Hybrid systems for thermoplastics

Hybrid system	**Technologies**	**Printable materials**	**Resolution**
5axismaker	Interchangeable heads for CNC milling FDM printing, Probe CMM	Thermoplastics	36 microns CNC xyz 0.6 mm FDM xy
Creality CP-01	Interchangeable heads for CNC milling FDM printing, Laser engraving	Thermoplastics	0.4 mm FDM xy 0.1-0.4 mm z
da Vinci 1.0 Pro 3-in-1	3D scanning, Interchangeable heads for FDM printing, Laser engraving	Thermoplastics	0.4 mm fdm xy 0.0125 mm positioning xy 0.0004 mm z positioning
Dobot MOOZ 2 PLUS	Interchangeable heads for: FDM 3D printing, Laser engraving, CNC carving	Thermoplastics	0.02 mm xyz CNC prepcision 0.4 mm FDM xy 0.05-0.3 mm z
H-Series by Diabase Engineering	FDM 3D printing, CNC milling	Thermoplastics	0.4-0.8 mm FDM xy 0.005 mm z, 0.01 mm mechanical repeatability
Snapmaker 2	FDM 3D printing, Laser engraving, CNC carving	Thermoplastics	0.05-0.3 mm z FDM
ZMorphVX	2-materials FDM 3D pritning Intercgangeable heads for CNC router, laser engraver, Thick paste extruder	Thermoplastics	0.2, 0.25, 0.3, 0.4 mm depending on printhead selection FDM xy Mechanical res positioning: 0.014 mm at x, 0.0006 mm at z layer resolution 50-400 microns

From the above, it can be seen that the development of hybrid systems technology for both metallic and polymer material has a huge growth rate in terms of the production of complex components with greater flexibility and maintaining high precision in a relatively short production time. Thus, with hybrid processes, new research avenues are opened to enhance the capabilities of the processes, minimizing the weaknesses that may arise by extending the scope of application.

The aim of the work is the development of a fully automated 5-axis hybrid CNC system for non-metallic material than combines conventional multi-axis CNC machining with extrusion based multi-axis AM. More specifically, the proposed machine design helps minimize set-up and dead-times through its overall automation, offers high accuracy AM/SM processes based on high-quality parts, improves tool head-type and tool carrying capacity and increases part production flexibility, all within a limited space, thus creating a new category of industrial-grade benchtop hybrid manufacturing systems with automated tool changer for high-end non-metallic products that need no or minimal post-processing.

3. Hybrid Manufacturing assessment

According to international standards (ASME AM223, DIN 8580), manufacturing processes can be divided into three categories: subtractive, additive and formative (Fig. 1) [3], [6], [32] [33]. More specifically, SM processes, such as turning, drilling and milling, start with a stock part or bulk material, removing material until the desired geometry is created. In AM processes, material is selectively deposited in successive layers until the final geometry is reached. Finally, in formative processes, such as casting and forging, the bulk material is shaped into the desired geometry through molds and tools. Table 2 presents a generic comparison of manufacturing processes categories.

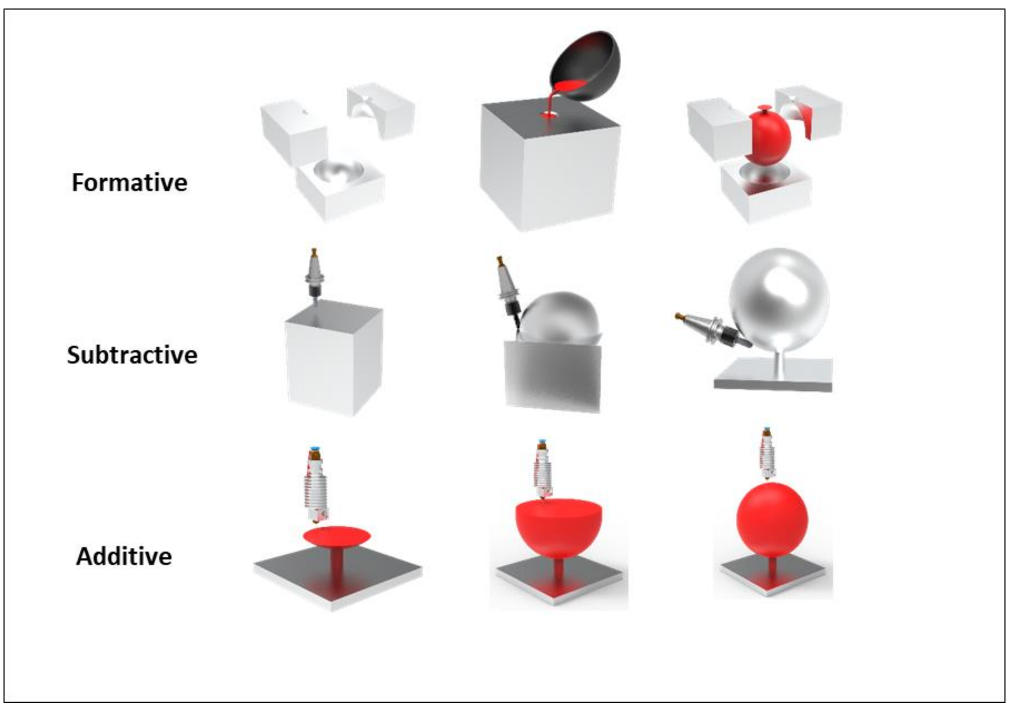

Figure 1: Formative, subtractive and additive manufacturing processes

Table 2: Comparison of manufacturing processes categories ([34],[35],[36]).

	Formative	**Subtractive**	**Additive**
Process	The material is formed into the desired shape by temperature and pressure, e.g. injection molding.	The desired part geometry is shaped by removing chips from bulk material through cutting tools, e.g. milling.	The material is built through phase change in a layer bylayer manner until the entire part is constructed, e.g. 3D printing.
Cost	Incomparable low cost to produce large volumes of identical parts, however the investment in tools (molds) is high.	Often the best choice for production low to medium volume components (10 to 100 parts). Initial investments in machinery are not cheap, but then individual spare parts can be produced at a relatively low price per unit.	Offers a cost-effective way to create intricately designed small or medium sized components that cannot be made with other manufacturing processes.
Lead Time	Steel tools for mass production are complex and their creation is time consuming, increasing part or batch delivery time to weeks.	Quick lead times, usually within 5 days.	Depends on the part, sizes, complexity, material, machine tool, needed post-processing etc.
Material properties	Ability to produce relatively complex components with high tolerances and a wide range of materials ideal for functional parts.	Almost anything with no internal features can be processed with great precision, with very tight tolerances and retains excellent material properties.	A number of materials available depending on the AM technology, however, it is generally not possible to produce spare parts with material properties equivalent to forming or material removal techniques.
Design Constrains	Design is limited by the need for mold features, such as spurs, runners, corner design and uniform wall thickness.	Many machines are limited to relatively simple geometries, although complex geometries become cheaper as technology evolves.	The parts can be produced with almost any geometry, complexity and internal features.

Manufacturing processes can be combined, thus creating hybrid fabrication processes. The most common hybrid production method is the serial combination of additive with subtractive processes. The component is built entirely through AM, almost to a roughly shaped geometry of the object, then subjected to a finishing SM process to perfect the object's surfaces and geometric tolerances. The second hybrid manufacturing method alternates iteratively between AM and SM during the construction process on an existing or a new object. AM and SM alternate either at every material layer or at every couple of layers to achieve accuracy in any external and internal geometrical features of an object, e.g. engine cooling pipes or mold cooling/heating channels.

Also, a hybrid system can combine materials, such as polymers, metals, composites, etc, during the additive stages and apply different ones for the creation of a single part thus creating what is called “multi-material parts” [3], [37], [38], [39]. However, this can be a serious challenge when melting temperature is significantly different between two materials, where special actions must be taken to successfully perform that [40]. A great deal of materials that can be used in additive processes, either as filament, usually polymers, such as ABS, nylon, PLA, PETG, etc, or as powder, metals, such as aluminum, copper, stainless steel and titanium, and polymers. As a result, by using different metals in a single multi-stage process, the workpiece acquires better characteristics without compromising its integrity. There are currently two types of HMT. The first is an off-the-shelf HMT offering both AM and SM, while the second is to add AM capabilities to a SM machine tool. By adding one or more AM heads to an existing CNC machine allows them to work in parallel with the standard set of subtractive tools. Although the total number of HMT available is still relatively small, as presented in the previous section, it is a technology that will only be expanded and developed, due to its inherent flexibility of combining both processes into one working space, which leads to increased productivity and ability to create parts that otherwise it is either impossible or very difficult to produce [8], [41], [42], [43], [44].

Hybrid technology offers several advantages over the material removal or additive process alone. Due to the ability to add material to existing parts, it allows the repair of damaged parts, since selective addition of material to the parts is performed. At the same time, AM allows the combination of different materials, changing its mechanical properties layer by layer which can improve its durability, e.g. car engine connecting rods. Besides, it reduces the need for extensive post-processing machining processes, as material is added only where required, for part finishing (Fig.2). Finally, the ability to switch between AM and SM without having to move the piece to another machine tool saves significant time and cost (set-up and down phases) and minimizes all related errors.

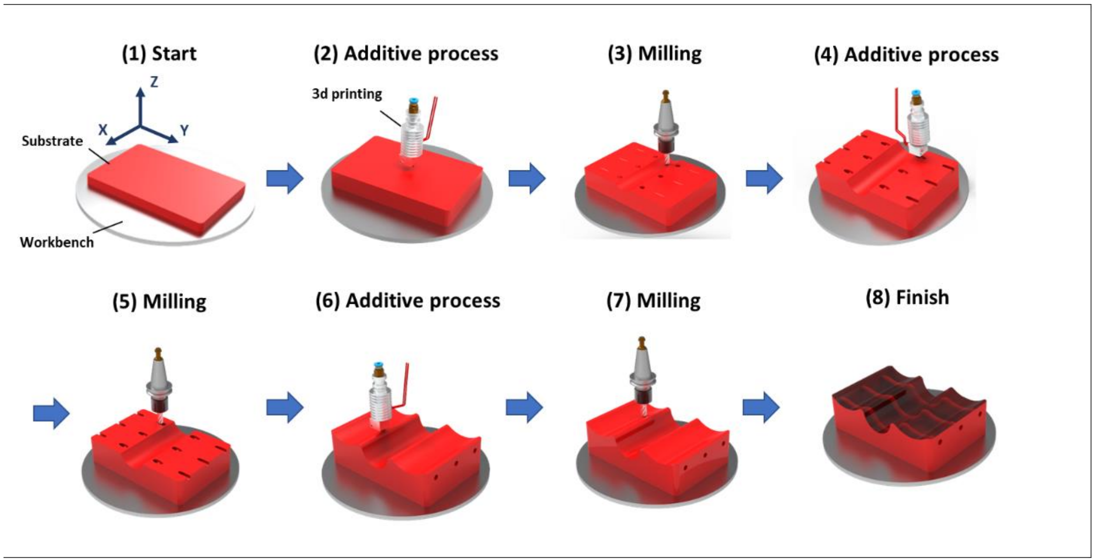

Figure 2: Schematic description of the hybrid AM and SM process.

As with any new technology, HM technology faces a set of pre-challenges, learning curve and questions. The first challenge is the investment and implementation cost associated with the equipment, and whether these costs can be kept low, so that any business can invest in a HMT. Also, another question that arises is whether HM technology is able to meet production requirements in a timely manner. HM has been proven in the production of models and unique parts in small batches, as well as in repairs of high quality and complexity parts. Custom on-demand production performed with HM eliminates the need of inventory and minimizes production time, thus resulting in overall cost reduction of the total production. Moreover, HM can effectively produce complex parts or perform complex repairs, e.g. in molds by adding material to enhance it for added durability. Over time, more and more industrial and other sectors are becoming aware of the benefits of using HM systems.

HM technology is at the beginning of a new technology leap, which fits smoothly with the Industry 4.0 transition that will dominate the manufacturing world in the following years. The combination of both AM and SM in one machine enables innovative ideas and leads to production disruption. Instrumental in the HM success is process optimization, which can be applied seamlessly, so as to provide design and manufacturing flexibility while maintaining strict specifications for the produced parts.

4. Multi-axis Hybrid Machine design

Design is a crucial stage in manufacturing parts for an assembly, as it determines manufacturing processes, cost, functionality and aesthetics of the overall product. At the same time, design must see to the manufacturing processes simplification for a machine's components, thus maintaining production and assembly at low-cost levels. As mentioned in the previous sections, the aim of this study is to design a machine that combines the operations of a 5-axis CNC machining center and a 5-axis extrusion 3D printer (Fused Filament Fabrication, FFF), which will be used for making polymer, elastomer and special type composite parts. Also, this machine should be able to build intricate part geometries that are difficult or impossible to produce with conventional means at a reasonable time (Fig.4) [45].

A HMT is a complex structure consisting of a number of functional mechanisms and sub-assemblies. Various materials can be used for the machine components, including ferrous and non-ferrous alloys and engineering plastics. Frame material must have enough strength to support the weight of the frame, the motors, the drive mechanisms and the spindle, as well as to withstand forces resulting from the machining process. Also, in order to avoid any deformations owing to static and dynamic loads, as well as thermal loads during operation, high rigidity of the machine frame is required. Stiffness is a crucial factor in design, as it affects the machining accuracy of the machine. In addition, moving parts and total weight is important because the mass of the frame contributes to both static and acceleration forces. Thus, a combination of proper cross section and material of the structural parts should offer the required mechanical properties and at the same time should be available at a low cost. Various materials were examined, including metals, mainly steel and aluminum alloys, and a number of plastics including high-density polyethylene, ultra-high molecular weight polyethylene. Their properties were collected, compared and evaluated as possible selection for the proposed HMT frame. Compared properties include coefficient of elasticity, density and yield strength. The ratio of elasticity to density was calculated to offer rigidity and the ratio of strength to density was introduced, so as to evaluate strength relative to weight. At the same time, costs for given part dimensions for different materials have been found retrieved from suppliers and are shown in Table 3 [46].

One of the most important issues that arose during the design of the proposed HMT was to determine how to both rotate the cutting tool shaft and adapt the extruder mechanism without an unnecessary increase in machine complexity. The idea is to change the cutting tool and extrusion head automatically, thus saving operation time and minimizing human intervention.

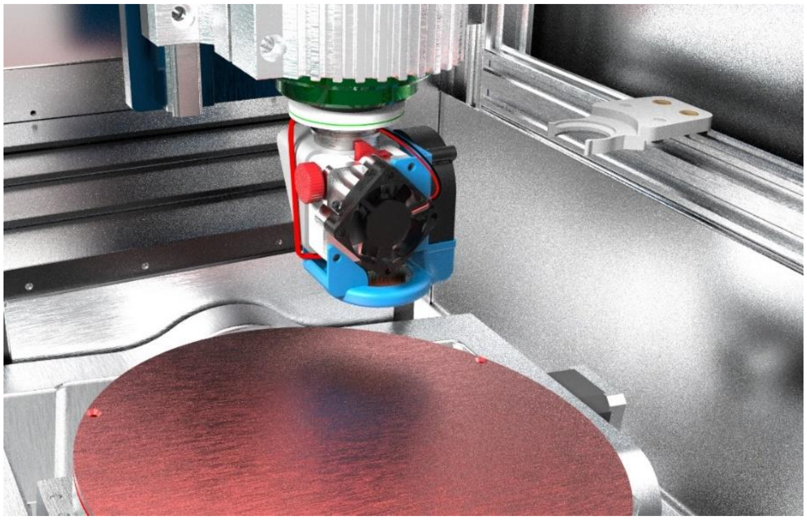

Figure 3: 5-axis Hybrid Machine Tool with automatic tool changing machine

Table 3: 5-axis Hybrid CNC Specifications

Proposed hybrid CNC specifications	
Working Area	200 x 200 mm
Travel x-y-z	210x210x150 mm
Table Size	200 mm
Swiveling range of A-axis	-45o ~ +45o
Rotary range of C-axis	360o
Swiveling speed of A-axis	30 rpm
Rotary speed of C-axis	100 rpm
Cutting Feed rate	900 mm/min
Rapid Feed rates (all axes)	1500 mm/min
ATC type	Linear Type
Tool magazine capacity	5 T
Max. tool length	120 mm
Max. tool diameter	Ø 10 mm
Max. tool weight	5 kg
XY Motor System	Timing belt and pulley (S2M) 2x24 Nema 17 stepper motor
Z Motion System	Ball Screw & nut SFU1605 1x Nema 17 stepper motor
Part Materials	Polymers, elastomers, special composites
Spindle Motor	HFSAC-6508-24-ER11
Spindle Speed	24000 rpm
Spindle Taper	ER11
Spindle Motor Output	0.8 kW
Spindle Weight	2.5kg
Total Weight	70 kg
External Dimension (LxWxH)	620 x 700 x 850 mm

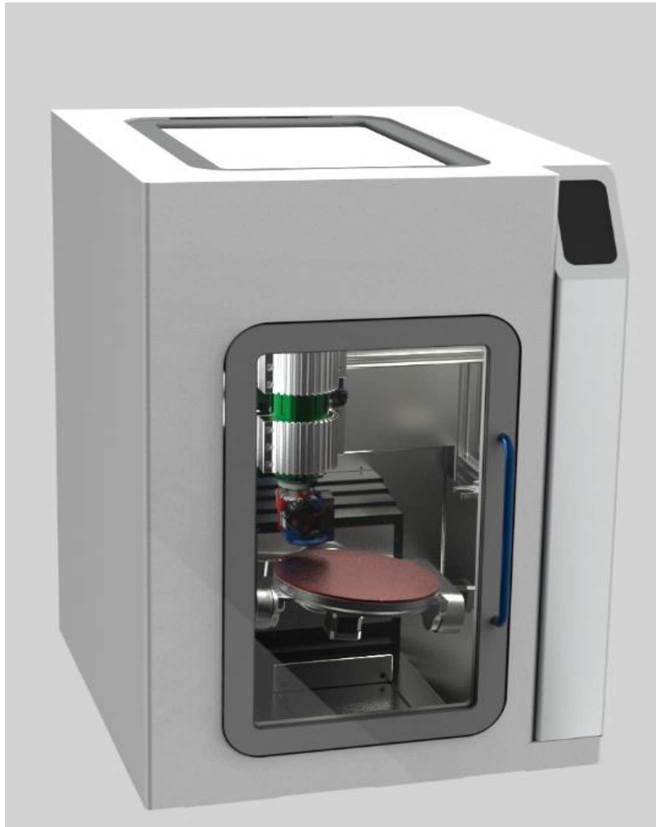

Figure 4: Desktop multi-axis hybrid milling-filament extrusion CNC machine tool

4.1 Structural material for the frame

Comparing metals and plastics is not easy, as metals have much higher strength and modulus of elasticity, but they also weigh more and are harder to process. It is important to note that both the studied steel and aluminum alloys, which are appropriate for the specific application have similar strength to weight properties, as indicated by the specific modulus E/ρ ratio, while high quality aluminum has significant strength advantage over weight. Following a material section process for the machine components, as proposed by Ashby, aluminum profiles were selected for quick and easy assembly [47]. Also, an advantage is the structural rigidity of aluminum profiles which is crucial for the accuracy of the machine.

Table 4: Material Properties comparison for structural parts [48]

Material	Density ρ g/cm^3	Tensile Yield Strength σ (MPa)	Modulus of Elasticity E (GPa)	Ultimate Tensile Strength σ_{max} (MPa)	Shear Modulus Sy (GPa)	Specific Tensile modulus E/ρ	Specific Tensile Strength Sy/ρ	Cost (US$/kilogram)
Aluminum 6061 -T5	2.7	185	69	310	2.56	25.50	9.63	2.30-3.50
Steel A36	7.85	250	200	550	79.3	25.47	10.1	0.55-0.68
polypropylene	0.92	33	1.4	460	0.4	1.52	0.43	1.31-1.55
Polycarbonate	1.22	62.05	3.1	65.5	5.03	2.54	4.12	3 – 6

Figure 5: The proposed 5-axis hybrid CNC frame.

4.2 Mechanical systems

The mechanical motion subsystems of a HMT CNC provide the means required for printing and machining of various materials. The choice of subsystem materials has a direct impact on performance, accuracy, repeatability, longevity and ultimately mechanical vibration transferred to the part. The mechanical motion subsystems consist of the drive system and the frame housing structure, each of which has a direct impact on the aforementioned properties on the HMT. In the rest of this section, we focus on the types of these systems and examine their advantages and disadvantages.

4.2.1 Guide Rail Design

The first part to be considered is the driving systems of the linear axes. The simplest chosen driving system (Fig. 6) includes guide blocks and linear guideway mount rails [49]. This system is capable of higher loading capacities with stability in handling balanced loads, along with orientation in any position, maintaining approximately the same load capacity due to its rigidity. The above features also make this system a perfect application for the specific purpose.

The most common linear guide includes square and round guide rails. Round guide rails were first created but do noy provide the precision offered by the square components of the guide rail. Round guide rails on the other hand are the preferred guide rails for vertical movement with heavy loads. Some of the problems arise from poor application or misuse. The main reasons for incorrect application often come from design miscalculation (load, speed, etc.) Most of the design problems have been overcome over time and materials have improved dramatically ([50],[51],[52]).

Square guide rails originally designed for CNC machine tool industry. They replaced the built-in guides that were part of the machine tool frame. However, this way of driving still provides high accuracy in some applications. Square guide rail is more rigid and stiffer, but they need constant support with strict requirements for flatness and parallelism, they cannot fill the gaps that a round guide rail can fill. The main advantage of square guide rails is their high placement accuracy. They maintain from 0.005mm to 0.025mm in length 3000mm compared to 0.25mm for round guide rail. They also manage this accuracy for an instant load. Most CNC router manufacturers choose the square rail despite the lower smoothness of their operation compared to the round ones because they receive higher loads with high accuracy [53].

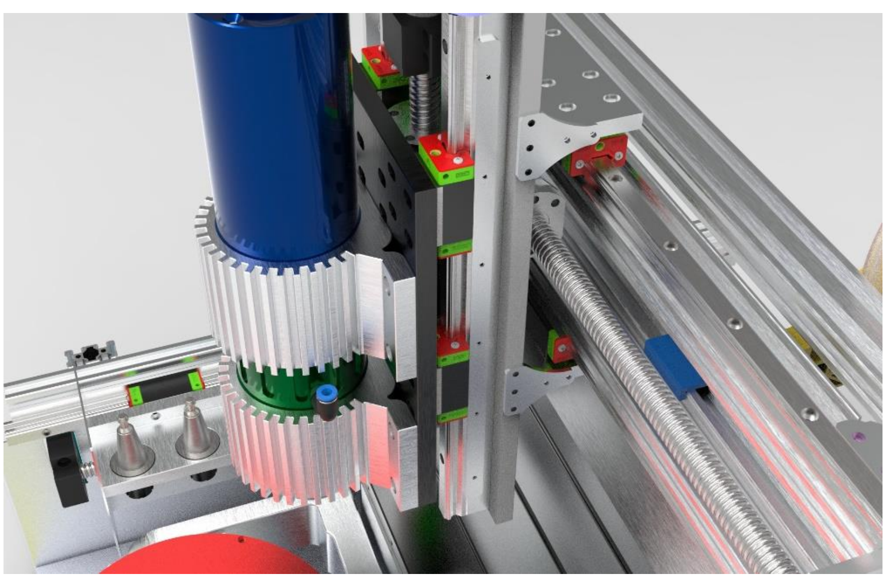

Figure 6: Mechanical motion systems and guide rails

4.2.2. Drive System

Feed drive system moves the axes and guides the workpiece to the desired positions in order to achieve the machining process on a machine tool. There are two types of feed drive systems: (a) direct and (b) indirect. In the direct drive system (Fig. 7), a linear motor is used to move the moving workpiece by the use of a magnetic field or compressed air. Although the magnetic mechanism provides high speed and acceleration when moving, in cutting conditions the maximum acceleration and loading capacity are severely limited as the cutting forces increase. In addition, there are pneumatic feed drives that operate on principle of converting the energy of compressed air into linear or rotational motion.

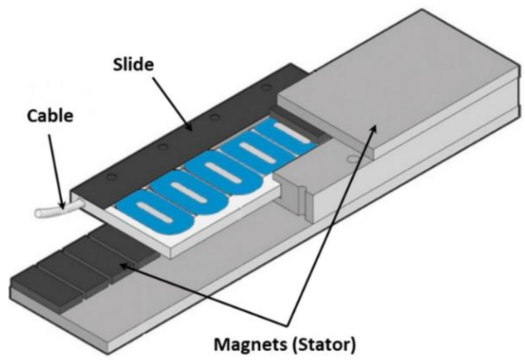

Figure 7: Direct feed drive system (linear motor) [54]

On the other hand, the indirect drive system (Fig. 8), a rotary motor moves the work table through a system that includes gear, ball-screw and nut system. The rotational motion of the motor translates into a linear rotation of the spheres between the screw shaft and the nut. There are two candidate electric rotary motor types that can be used to drive the axes of the proposed machine tool, keeping in mind the low cost and the high precision: (a) servomotors and (b) stepper motors (Fig.9), both of which have their own strengths and weaknesses. While servomotors have a feedback drive system, stepper motors have multiple methods to be driven. Although both are similar in terms of control, there are major differences in performance and applications. Table 5 provides an abstract performance comparison of the two motor types [55]. Indirect drive systems show high rigidity of the system against the developing forces during machining process. Although this mechanism has limited speed and acceleration ability, the mechanism retains its acceleration ability for a wide range of inertia variations. The high efficiency load capacity, the long shift path, the low heat dissipation of the systems in combination with the long life, make the wide application of the system in the machine tool industry [56][57][58][59].

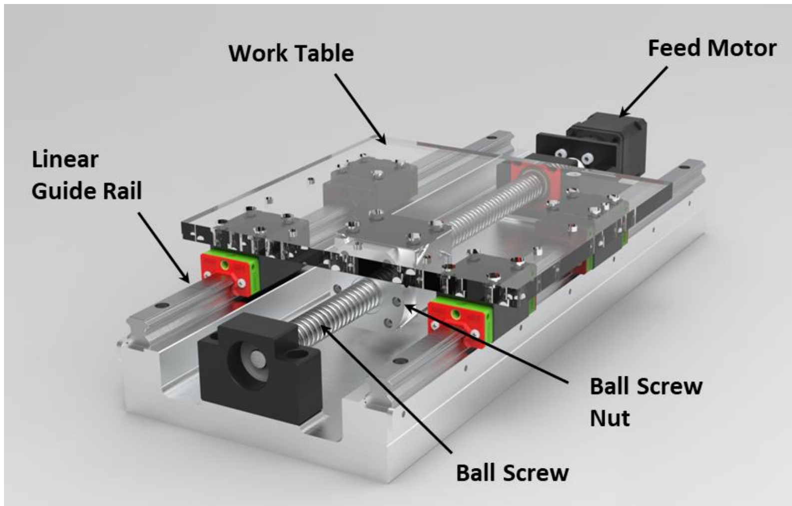

Figure 8: Indirect feed drive (ball screw, motor and linear guides)

Although a number of actuators have been used for CNC machine tools in the past, together with the hydraulic actuators, which are mainly used for very high powers and large machine tools, electric motors are the most common for axes drive in CNC machine tools. The proposed HMT is small in size, so hydraulic actuators cannot and need not be utilized.

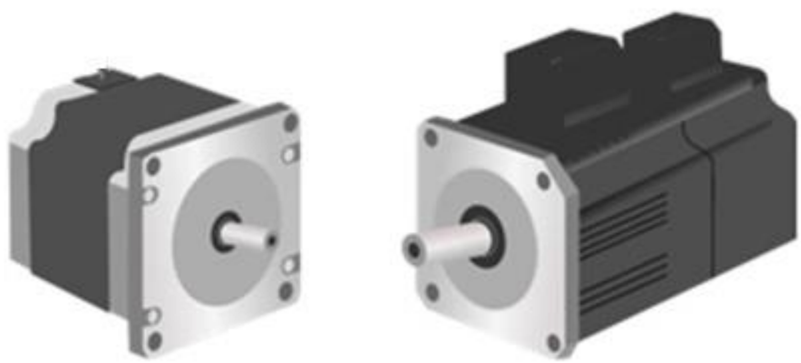

Figure 9: Stepper (left) and servo motor (right) [60]

Table 5: Servo versus stepper motors [61]

	Advantages	Disadvantages
Stepper motor	• Simple design control • No feedback required • Excellent low speed torque • Excellent low speed smoothness • Lower overall system cost • Longer Life • Excellent Repeatability • Provide full torque at standstill • Very reliable • Low-speed synchronous rotation	• Torque decreases as speed increases • Constant current regardless of requirements • Cannot react to changes is load • Low efficiency • Torque declines rapidly with speed • Low Accuracy • Very noisy
Servo motor	• Closed loop control • Higher torque at higher speed • Lower motor heating • Better choice for variable load systems	• More complex control – tuning required • Position feedback required • Higher overall system cost • Poor motor cooling

	• High efficiency • Hight output power relative to motor size and power • Encoder determines accuracy and resolution. • Resonance and vibration free operation • High speed operation is possible	

Stepper motors are a good choice whenever low-cost controlled motion is required. They can be used in applications where you need to control rotation angle, position and synchronization. Due to the inherent advantages mentioned in Table 6, stepper motors have found many applications, including printers, laser cutters, engravers and others. Stepper motors have a number of features that make them the motor of choice for a wide range of applications, mainly in measurement and control. There are low costs that produce high torque at low revolutions and benefit from a simple structure. The advantage of open loop operation is that as long as the motor is operating within its specified torque, the shaft position is always known without the need for a feedback loop [62] [63].

There are several factors to consider when choosing a stepper motor for our application ([60],[64],[65]):

1. Starting torque
2. Maximum speed
3. Duty cycle
4. Required power
5. Load inertial
6. Speed control
7. Reversible motor
8. Time to accelerate
9. Time to decelerate
10. Size and weight consideration

4.2.3. Power transmission mechanism

The purpose of the drive mechanism is to transfer the torque provided by the electric motors for the linear movement of the machine axes. These systems offer a simple and compact means of power transmission and drive with exceptional reliability. There are two main types: (a) power screw (ACME THREAD, Fig. 10) and (b) ball screw. However, the differences arise in the efficiency with which the motion is transmitted, friction power losses and the respective thermal phenomena, accuracy and backlash elimination, the permissible rotation speed and the required linear speeds. At this point, it is necessary to analyze the particularities of each type of screw.

Power screws (Fig. 10) have trapezoidal thread to roll on to the lead screw. As the motor rotates, the thread pushes the shaft nut forward or backward depending on the direction of rotation. This transforms motor's rotary motion to linear motion on the shaft.

Ball screws (Fig. 10) provide many advantages in their applications. Although the basic screw and nut principle applies, the contact between them is achieved though the intermediate balls, that recirculate. With the right nut material, ball screws can achieve self-lubrication. For example, if the application which provides low friction force, polymer nuts are used. This can reduce or even eliminate the need for lubrication. On the contrary, metal nuts can carry higher loads, but they will also have a higher friction force and require lubrication [66]. Table 6 shows the advantages and disadvantages of the two types of screws that are used for transferring torque ([67], [68], [69], [70]).

Table 6: Advantages and disadvantages of power transmission screws [71]

	Advantages	Disadvantages
Power Screw (ACME)	• Low cost • Self-locking (do not require a braking system) • More suitable for vertical applications • Lower operating noise • Prevent backlash drive • Self-lubricating	• Generally, less efficient, requiring greater torque and a larger motor and drive • Higher friction and higher operational temperature • Replaced more frequently
Ball screw	• Hight efficiency • Predictable life expectancy • Precise and repeatable movement • No tendency for slip-stick • Minimum thermal effects • Easily preloaded to eliminate backlash with minimum friction penalty • Smoother movement over full travel range • Smaller size for same load	• Requires higher levels of lubrication • Tend to overhaul – Needs additional brakes if locking is required • Susceptible to contamination • For the same capacity ball screws are not as rigid as conventional power screw

CNC machine tools that are found in the market today use both power and ball screws. Most low-cost machines use power screws for cost saving and design simplicity reasons. However, as speeds increase and high reliability requirements are set, power screws become more common. The choice must be weighed against capabilities and costs, in order to determine the optimal drive mechanism for the system.

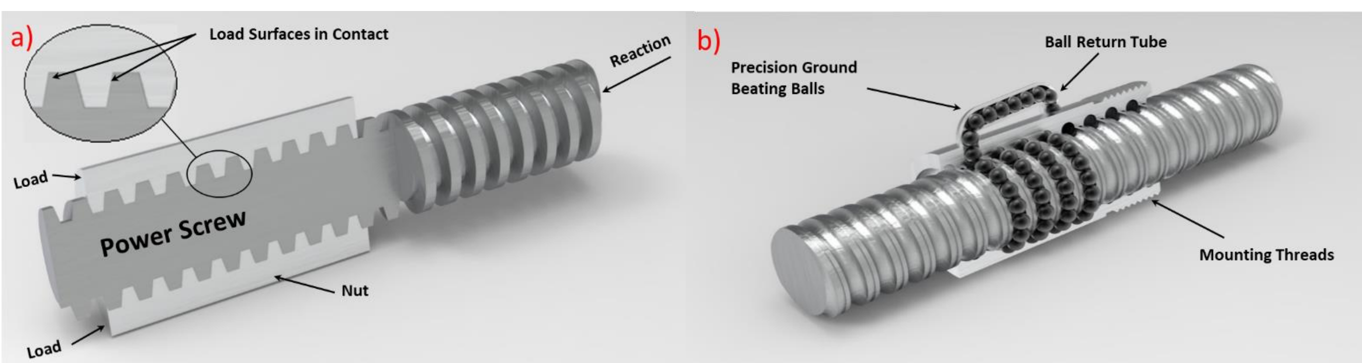

Figure 10:(a) Trapezional Power Screw, (b) Ball Screw

4.2.4. Hollow Rotary Table

Hollow rotary table (Fig. 11) is a rotary load device. It uses spiral conical gears whose contact teeth design offer uniform loading, thus, high torque and high transmission efficiency, high accuracy and high-cost efficiency. Combined with a planetary reducer, the transmission ratio reaches 1:180. Mounting accuracy is comparable to the direct drive motor which can carry the idle load in a short time [72]. A cross-roller bearing is used in the hollow table, which allows both high load and high rigidity. Tables and arms can be installed directly on the output table. This saves design time and construction cost of an installation mechanism, installation of necessary mechanism components, voltage adjustment of a belt, etc, when mechanical components such as belt and pulley are used for installation. The large diameter of the output table hole helps reduce complexity of wiring and piping, thus simplifying the design of equipment. The design of the hollow table was based on the SV type of GIGAGER Hollow Rotary Table [73][74].

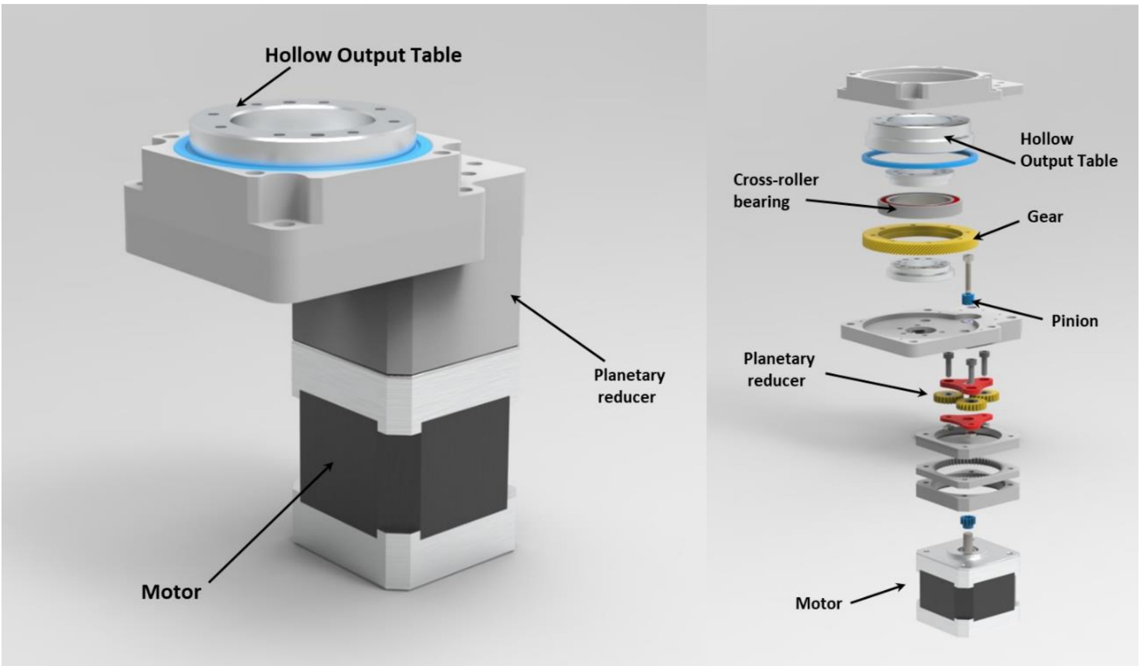

Figure 11: Hollow Rotary Table

5. Analysis of CNC milling machine frame

HMT are machines that perform both SM and AM processes. However, in terms of mechanical loading, the SM processes, such as milling, drilling, turning etc, are the ones that load a HMT significantly, as compared to the AM ones, whose main loading is thermal. When cutting tools are involved, cutting forces can affect both the part processing and the structure of the machine tool itself. Cutting tools in CNC machining are used for removing large quantities of material during the roughing phase and for providing the necessary surface smoothness as well as for perfecting the geometric features of a workpiece during the finishing phase. Vibrations that appear during these phases are determined by machine tool stiffness and strength, so they must be taken into account at the machine design stage. Unwanted vibrations (chattering) between tool and workpiece also affect the quality of the final surface during finishing. Chatter is one of the most critical features considered during the design process of a machine ([75],[76],[77]). Static and dynamic deformations of the machine tool play important role in the integrity of tolerance and stability during the machining process that affect workpiece quality, machine productivity and accelerate tool wear.

Modal analysis is the study performed for analyzing a structure under vibration conditions. The behavior of the structure in a given frequency range can be modeled as a set of individual vibration modes. To be easily understood for any structural vibration problem, the eigen-values and eigenfrequencies of a structure must be identified and quantified. Some parameters, such as natural frequency and resonant frequency are used to describe this effect. From the use of modal parameters to model the problem, the natural frequencies that cause the tuning of the structure can be examined, thus improving the machine design. Modal analysis is one of the main tools for analyzing the dynamic behavior of structures, thus optimizing design of structural elements that a machine comprises of ([78],[79]).

In order to evaluate structural performance of the proposed CNC HMT, the finite element method (FEM) was used to model the static and dynamic behaviors under different loading conditions. Figure 12 shows the complete model of the structure of the machine and all structural simplifications used for the preparation of the analysis model (simplified). Due to the complexity of the design, a simplified model for Finite Element Analysis (FEA) was created, which combines structured (rotating symmetrical parts) and unstructured elements (aluminum profiles). Adjacent joints have been achieved by merging selected nodes, by inserting a rigid connection (replacing screw connections) or by integrating linear springs between corresponding pairs of nodes (connection between linear guides and carriages or their drive screws). The loading conditions implemented for the analysis were as follows:

1) Static analysis under gravity forces, without any external load.
2) Static analysis under gravity, external force 100N applied (piece weight) to the table and external force 50N applied to the shaft tip in the Z direction (tool weight).
3) Static analysis under gravity force, and external forces, and external force applied external forces 100N to the table in the direction X, Y, and Z simulating the cutting force at different angles of the table in A and B directions.
4) Frequency analysis and harmonic analysis for the dynamic response to natural frequencies, as well as to forces created during the cutting process

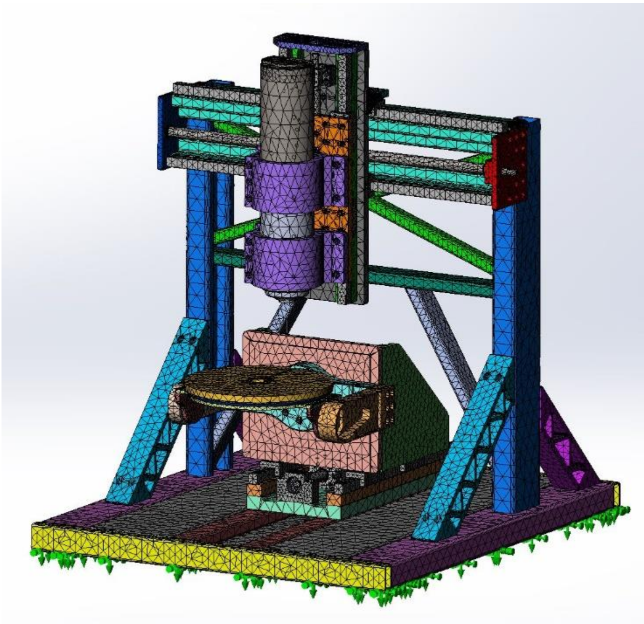

Figure 12: Finite element model of 5-axis hybrid machine

5.1 Static analysis

Static analysis shows the behavior of the structure, when acting forces are constant. From the static analysis we obtain the deformations of the structure, stresses that are created and possible failure at rest. Creating a proper mesh is important for the accuracy of the results, as in any FEA. Due to the complexity of the machine tool structure, a simplified FE design model was created by combining a structured and unstructured mesh. After the meshing process, the total elements generated were 455,224 and the number of nodes were 659,338. The boundary conditions used for all three degrees of freedom are at the base of the machine tool, the beams of which are fixed, i.e., all degrees of freedom are set to zero (Fig. 12). The model was subjected to forces, such as the part weight, the tool and spindle weight and finally the forces during cutting, in various table angles in A and B directions under the influence of gravity. The structure was examined in two different cutting conditions, the first is cutting forces during 3-axis machining and the second during drilling. Table 7 and 8 present static analysis results.

Table 7: Static analysis results (endmill cutting forces)

No.	**Table Angle**		**Von Mises (N/mm^2)**	**URES (mm)**	**Equivalent Strain ESTRN**	**FOS**
	A	**B**				
1	0	0	1.337e+07	2.399e-01	8.314e-05	1.085e+01
2	22.5	0	1.308e+07	2.399e-01	7.999e-05	1.108e+01
3	22.5	22.5	1.337e+07	2.399e-01	8.312e-05	1.085e+01
4	45	0	1.337e+07	2.399e-01	8.313e-05	1.085e+01
5	45	45	1.309e+07	2.398e-01	8.000e-05	1.108e+01

Table 8: Static analysis results (drill cutting forces)

No.	**Table Angle**		**Von Mises (N/mm^2)**	**URES (mm)**	**Equivalent Strain ESTRN**	**FOS**
	A	**B**				
1	0	0	7.551e+06	1.516e-01	7.822e-05	1.920e+01
2	22.5	0	8.649e+06	1.521e-01	6.641e-05	1.677e+01
3	22.5	22.5	8.563e+06	1.746e-01	7.977e-05	1.693e+01
4	45	0	1.080e+07	1.519e-01	9.056e-05	1.342e+01
5	45	45	8.439e+06	1.848e-01	7.591e-05	1.718e+01

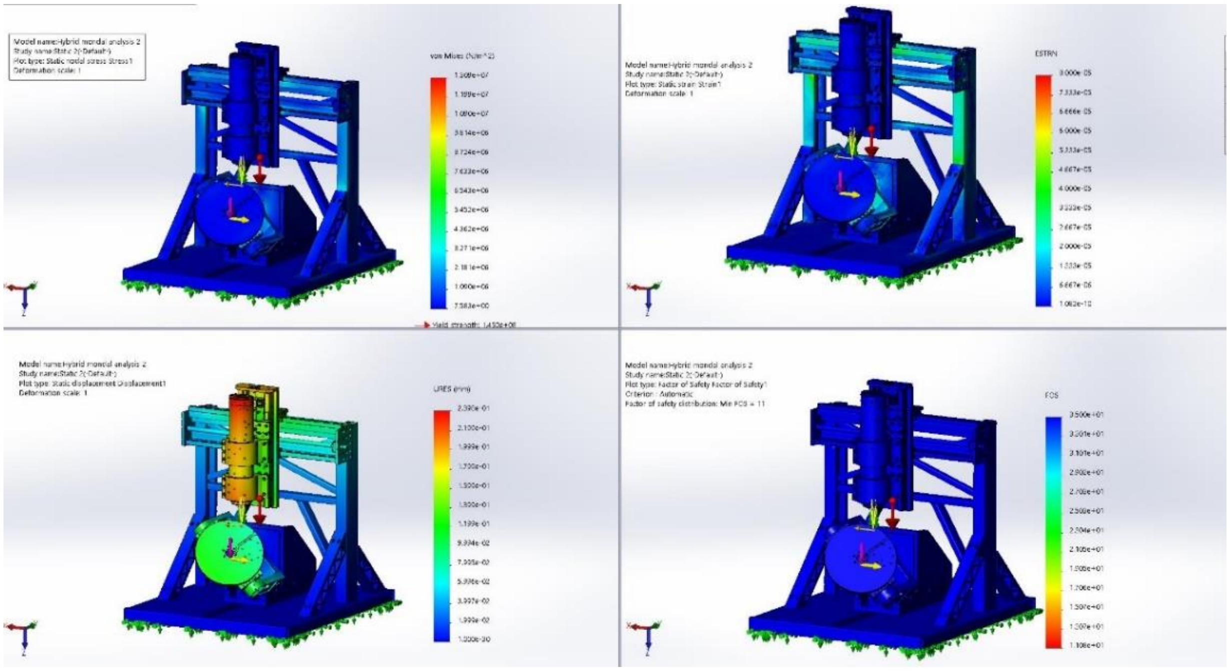

Figure 13: Static analysis results for table angles A 45º and C 45º

After simplification of machine tool structure, total weight of the frame is 20kg. Thus, the entire deformation of the Z-axis beam was evaluated. The overall deformation under the weight is low and does not affect the accuracy of machine tool. To investigate the deformation caused by the cutting force, the selected spindle had a torque of 0.35Nm, 1.1kw of power and a maximum rotation speed of 24000 rpm. The axial momentum load applied to the tip of the spindle that bears an 8mm diameter end-mill was T = 0.35Nm, force load of F = 100N in all X, Y and Z directions and at the same time the most unfavorable angle of the table (for A and C rotation angle of 45º). These loads are the maximum applicable ones for the specific machine design. Table 7 shows the results from the static analysis, showing that the maximum deformations are of the order of 0.24 mm for the worst-case scenario, which is too small to affect the actual cutting accuracy. Since the machine tool is designed to process only soft material, it is almost unlikely that forces of this order will develop, which makes the machine tool rigid enough within the specified operational values.

5.2 Frequency response functions

Dynamic behavior reflects the structure’s resistance to vibration. Therefore, a dynamic analysis was performed to determine the natural fundamental frequencies, which is predicted for the machine tool model (Fig. 14, 15, 16). Natural frequencies indicate the dynamic characteristic of the joint is one of the key factors influencing the dynamic performance of the machine tool. Accurate calculation of the stiffness parameters of the joints in the power supply system at the design stage of the machine tool is crucial for obtaining correct results of theoretical analysis. Table 9 lists the first twelve critical eigenfrequencies of the structure.

Table 9: Natural frequencies

Mode No.	Frequency (Hertz)	Revolution per minute (RPM)
1	50.111	3006.66
2	58.505	3510.30
3	81.507	4890.42
4	142.330	8539.80
5	152.160	9129.60
6	187.660	11259.60
7	245.790	14747.40
8	317.250	19035
9	346.350	20781
10	351.320	21079.20
11	359.76	21585.60
12	390.23	23413.80

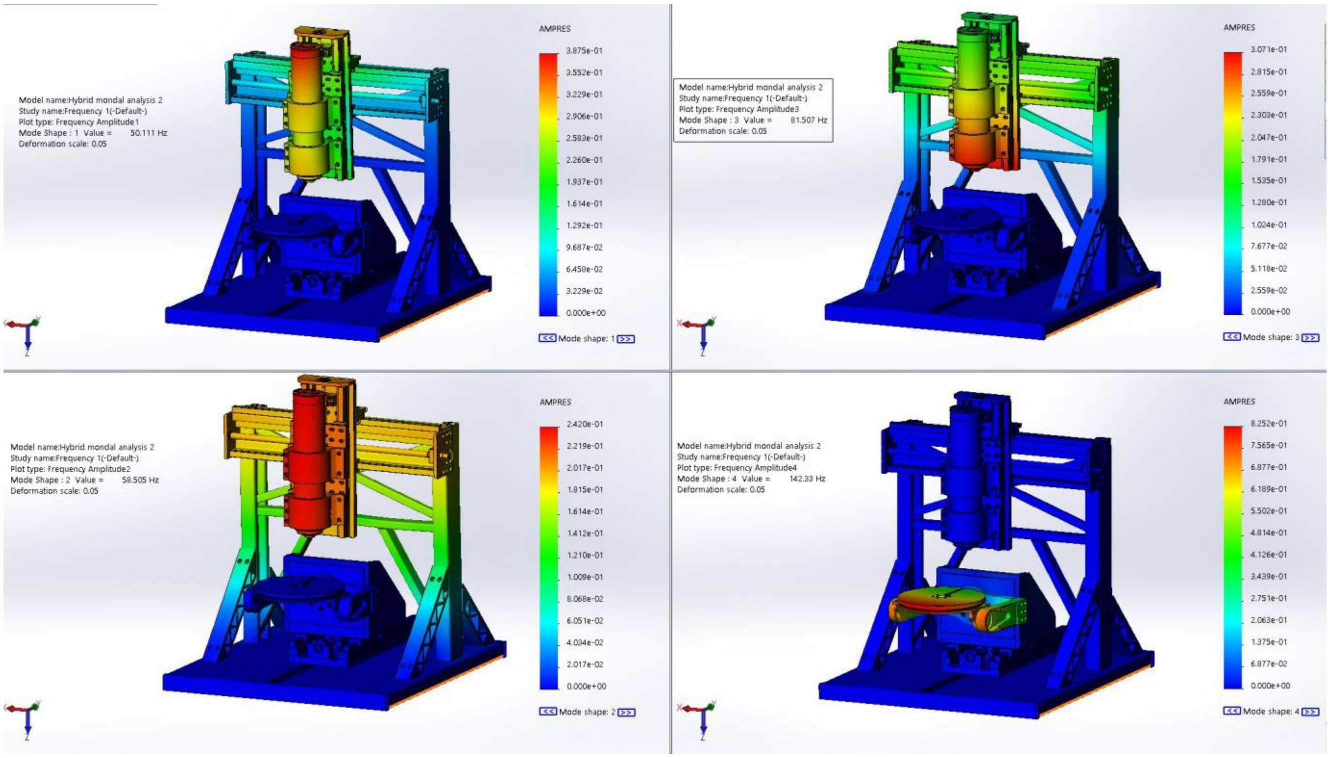

Figure 14: Natural frequencies of first for four frequencies: a) 50.111Hz, b) 58.505Hz, c) 81.507Hz, d) 142.330Hz

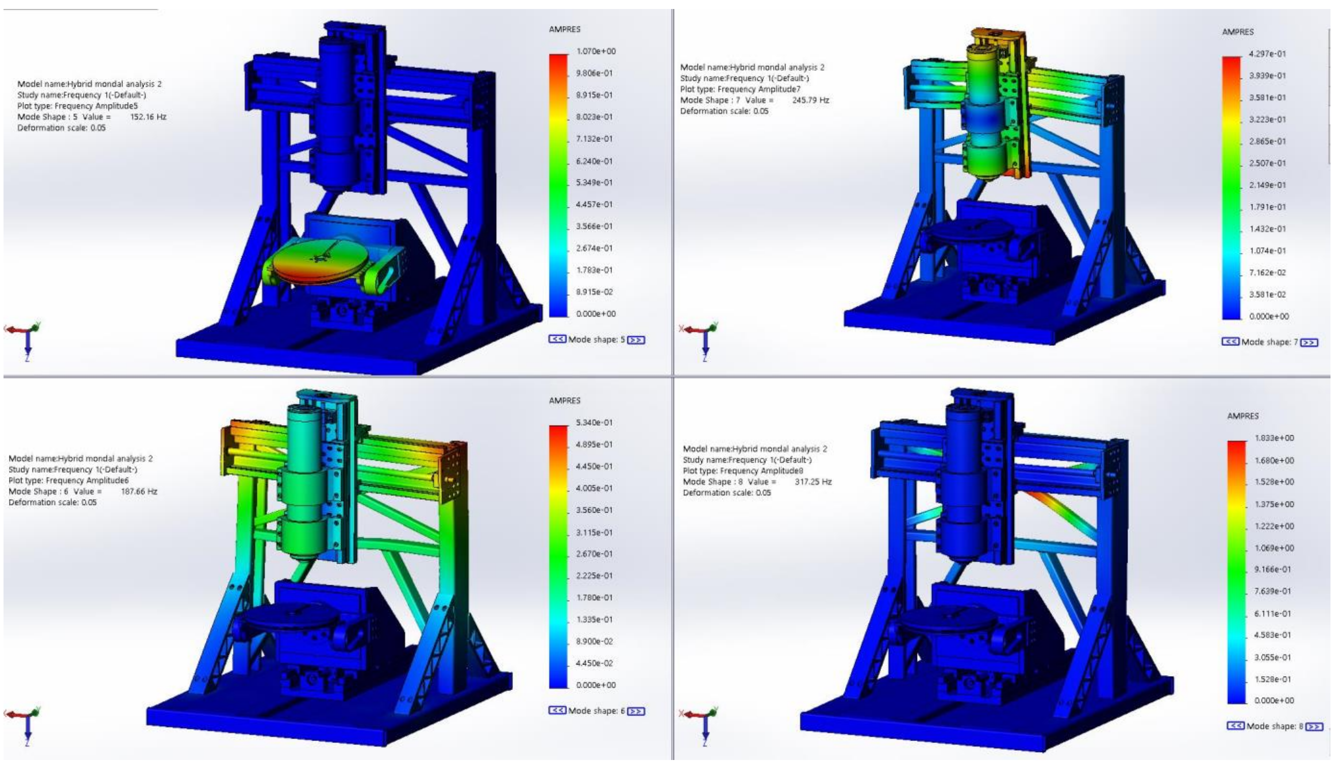

Figure 15: Natural frequencies of first for four frequencies: e) 152.160Hz, f) 187.660 Hz, g) 245.790Hz, h) 317.250Hz

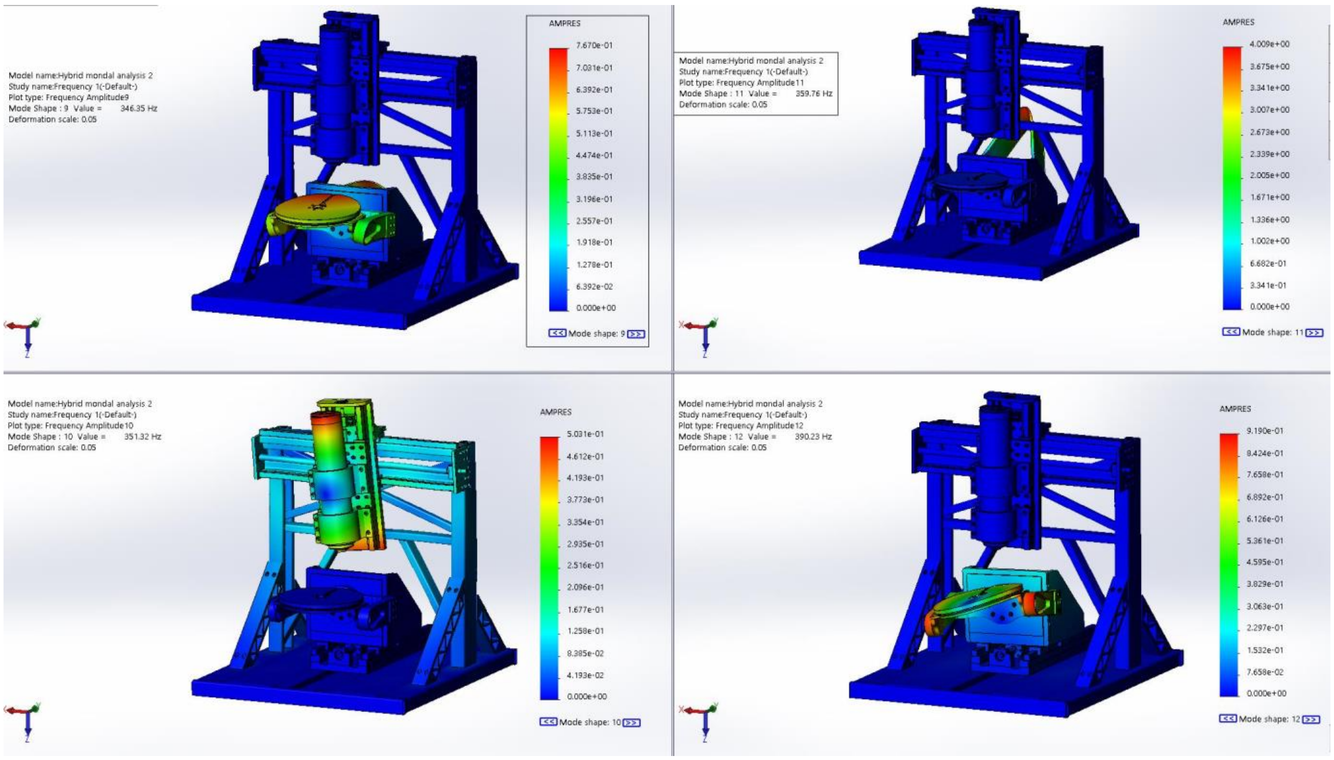

Figure 16: Natural frequencies of first for four frequencies: i) 346.350Hz, k) 351.320Hz, l) 359.760Hz, m) 390.230Hz

The first three critical frequencies appear at 50.111Hz, 58.505Hz, 81.507Hz, which are observed in the lower section of the spindle, supported by the vertical columns in the X-Z plane. The fourth and fifth critical frequencies at 142.330Hz and 152.165Hz respectively are observed in the outer rim of the table. The sixth and seventh critical frequencies occur at 187.660Hz and 245.790Hz and are observed at the spindle, associated with the vertical column around the vertical Z axis. The eighth critical frequency is displayed at 317.250Hz with a displacement of 1.833mm, observed at the inclined supports of the machine back. The ninth critical frequency is displayed at 346.35Hz with a displacement of 0,0767mm in the arms of the machine table. Subsequent frequencies cannot be considered critical, as they lie outside the operating range of the machine tool. In all, deformations are very small and do not affect the machining accuracy, at the same time the frequencies can be avoided if the operating spindle speeds do not match them, thus avoiding unfavorable operating conditions. Table 10 lists all the critical eigenfrequencies and how they affect the structure.

Table 10: Frequency analysis results

Mode No.	Natural Frequency (Hertz)	Total Defromation (mm)	Relative movement
1	50.111	3.875e-01	X-Z travel axis
2	58.505	2.420e-01	X-Z travel axis
3	81.507	3.071e-01	X-Z travel axis
4	142.330	8.252e-01	Tip of the table
5	152.160	1.070e+00	Tip of the table
6	187.660	5.340e-01	X-Z travel axis and upright of structure
7	245.790	4.297e-01	X-Z travel axis
8	317.250	1.833e+00	Compressive strut (back of machine)
9	346.350	0.767e-01	Table and compressive strut of table
10	351.320	0.5031e-01	X-Z travel axis and upright of structure
11	359.760	4.009e+00	Compressive strut of table
12	390.230	9.190e-01	Table

5.3 Harmonic Response Analysis

The machine assembly model was subjected to dynamic loads, which simulate the actual machining process, thus the behavior of the structure under varying loads was examined. The dynamic analysis was performed by subjecting the structure to cyclic (harmonic) loading, resembling simulated processing conditions. It was examined whether the harmonic frequency is identical with the natural frequency of the structure, so as to avoid resonance of the structure to the maximum allowable amplitude. This state of resonance should be avoided as maximum vibrations can lead to excessive stress or in extreme cases damage (failure) to the structure. The structure was analyzed using the FEM for the harmonic response analysis. Loads were applied according to design requirements. The undertaken cutting conditions refer to cutting loads for pocket machining with D=8mm (tool diameter), N_z=2 (number of flutes), λ_s=30^o (helix angle), $f_z = 0.05$mm/tooth (feed per tooth per revolution), a_p=2mm (axial depth of cut), a_e=2mm (radial depth of cut), n=3600 rpm (revolutions per minute). The cutting model was obtained by ([80], [81], [82]), but since rotational velocities were small according to the implemented spindle and supposed cutting material, we doubled them in the model. The results showed that the structure is able to withstand the harmonic load in tuning frequencies. Therefore, the design of the structure is considered to be safe from harmonic loading. Table 11 shows the results of harmonic analysis

Table 11: Harmonic analysis results (endmill cutting forces)

No.	Table Angle		Von Mises (N/mm^2)	URES (mm)	Velocity (mm/sec)	Acceleration (mm/s^2)	FOS
	A	B					
1	0	0	8.394e+06	5.137e-02	1.538e-02	3.237	1.727e+01
2	22.5	0	7.256e+06	5.138e-02	1.538e-02	3.237	1.998e+01
3	22.5	22.5	6.310e+06	3.375e-02	1.538e-02	3.237	2.298e+01
4	45	0	7.099e+06	6.066e-02	1.537e-02	3.237	2.043e+01
5	45	45	6.447e+06	3.211e-02	1.538e-02	3.236	2.245e+01

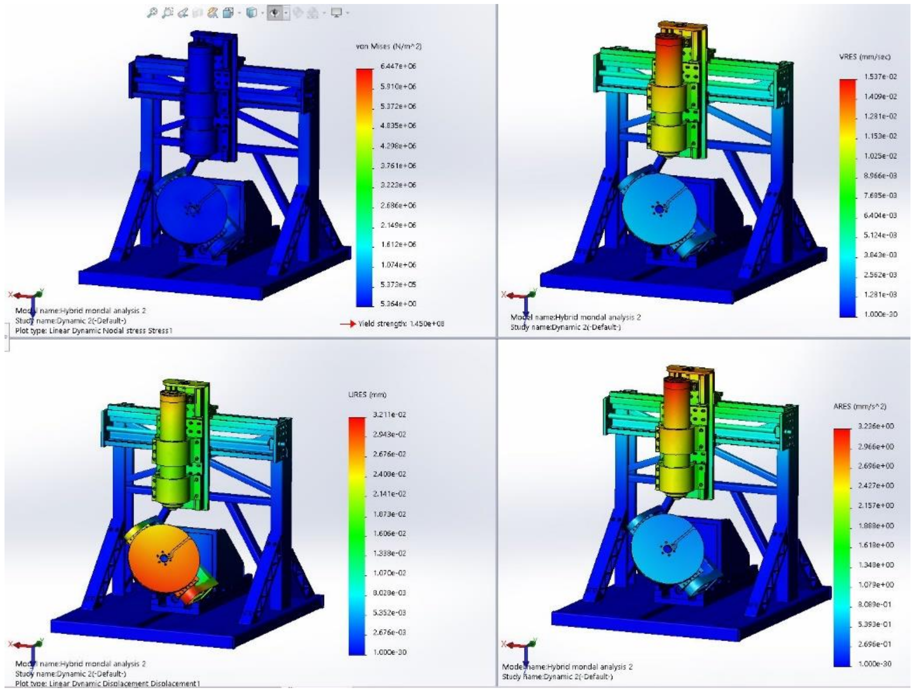

Figure 17: Harmonic analysis results for table angle A 45º and C 45º

After identifying the natural frequencies and their vibration modes, harmonic response analyses were performed to quantify the steady state response of the machine to loads that vary harmoniously with time. In addition, nonlinear parameters, such as damping, were applied to the spindle tip and responses were evaluated for different eigenfrequencies. Harmonic response analysis is able to verify whether the behavior of the structure is able to successfully overcome the tuning and the harmful effects of forced self-excited vibrations. The equivalent forces predicted by the load modeling were converted to a harmonic form applied to the machine. Maximum deformation observed at the rim of the machine tool table (angles A 45º – C 0º) during vibration was 0.06mm. The results of the dynamic analysis and evaluations of the structure are acceptable and well within intended operating limits.

6. Conclusion

In recent years, a couple of CNC machine tool and 3D printer manufacturers have developed hybrid multi-axis machine tools for parts of intricate geometry, which need to be durable and precise, so as to minimize processing times, material waste during the rough milling phase, the need for post-processing by hand or on other equipment and all related costs. However, this has been implemented in either heavy industry equipment of extremely high acquisition, production and maintenance costs or home (non-professional) equipment with low processing repeatability and part quality. Although, implementation of Hybrid Manufacturing processes has proven to be quite efficient in producing commercially ready parts that require none or minimal post-processing, there is not a appropriate machine tool in the market which is both efficient, cost effective and capable of producing quality parts. The very high acquisition and production cost of industrial hybrid machine tools, however, is not in line with everyday industrial or artisanal practice of producing small batches of limited-cost pieces from non-metallic materials.

This paper aims at addressing the gap in the hybrid manufacturing sector and presents a design and analysis study for a new desktop multi-axis hybrid machine tool, that creates finished products made of polymers, elastomers and special type composites. The machine combines 5-axis Subtractive Manufacturing, specifically milling and drilling operations, with 5-axis Additive Manufacturing, specifically Fused Filament Fabrication 3D printing technology with an automated tool change system. The structural, as well as the moving, elements that comprise the machine were designed and selected with the aim of simplifying their production and the machine assembly, so that the total production cost of the machine remains low. The performed static, frequency response and harmonic response analyses indicate that the behavior of the proposed structure is rigid and stiff enough for cutting soft materials, thus making it a viable and low-cost solution for small batch manufacturing of polymer, elastomer or special composite products that need no further post-processing either for engineering, industrial or artistic applications.

References

[1] P. J. G. Nieto, E. García-Gonzalo, C. O. Galán, and A. B. Sánchez, “Hybrid ABC optimized MARS-based modeling of the milling tool wear from milling run experimental data,” *Materials (Basel).*, vol. 9, no. 2, 2016, doi: 10.3390/ma9020082.

[2] M. Merklein, D. Junker, A. Schaub, and F. Neubauer, “Hybrid additive manufacturing technologies - An analysis regarding potentials and applications,” in *Physics Procedia*, 2016, vol. 83, pp. 549–559, doi: 10.1016/j.phpro.2016.08.057.

[3] J. B. Jones, “The Synergies of Hybridizing CNC and Additive Manufacturing,” 2014.

[4] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, “Additive manufacturing (3D printing): A review of materials, methods, applications and challenges,” *Composites Part B: Engineering*, vol. 143. Elsevier Ltd, pp. 172–196, Jun. 15, 2018, doi: 10.1016/j.compositesb.2018.02.012.

[5] A. Ewald, T. Sassenberg, and J. Schlattmann, “Evolutionary-based optimization strategy in a hybrid manufactured process using LMD,” in *Procedia CIRP*, 2018, vol. 74, pp. 163–167, doi: 10.1016/j.procir.2018.08.070.

[6] S. T. Newman, Z. Zhu, V. Dhokia, and A. Shokrani, “Process planning for additive and subtractive manufacturing technologies,” *CIRP Ann. - Manuf. Technol.*, vol. 64, no. 1, pp. 467–470, 2015, doi: 10.1016/j.cirp.2015.04.109.

[7] T. Yamazaki, “Development of A Hybrid Multi-tasking Machine Tool: Integration of Additive Manufacturing Technology with CNC Machining,” in *Procedia CIRP*, 2016, vol. 42, pp. 81–86, doi: 10.1016/j.procir.2016.02.193.

[8] M. Müller and E. Wings, “An Architecture for Hybrid Manufacturing Combining 3D Printing and CNC Machining,” *Int. J. Manuf. Eng.*, vol. 2016, pp. 1–12, Oct. 2016, doi: 10.1155/2016/8609108.

[9] J. Do Suh and D. G. Lee, “Design and manufacture of hybrid polymer concrete bed for high-speed CNC milling machine,” *Int. J. Mech. Mater. Des.*, vol. 4, no. 2, pp. 113–121, Jun. 2008, doi: 10.1007/s10999-007-9033-3.

[10] T. C. Chen, Y. J. Chen, M. H. Hung, and J. P. Hung, “Design analysis of machine tool structure with artificial granite material,” *Adv. Mech. Eng.*, vol. 8, no. 7, pp. 1–14, 2016, doi: 10.1177/1687814016656533.

[11] K. P. Rajurkar, D. Zhu, J. A. McGeough, J. Kozak, and A. De Silva, “New Developments in Electro-Chemical Machining,” *CIRP Ann.*, vol. 48, no. 2, pp. 567–579, Jan. 1999, doi: 10.1016/S0007-8506(07)63235-1.

[12] “Kozak: Hybrid machining process evaluation and development - Μελετητής Google.” https://scholar.google.com/scholar_lookup?title=Hybrid Machining Process Evaluation and Development&publication_year=2000&author=J. Kozak&author=K.P. Rajurkar (accessed Jan. 03, 2022).

[13] D. K. Aspinwall, R. C. Dewes, J. M. Burrows, and M. A. Paul, “Hybrid High Speed Machining (HSM): System Design and Experimental Results for Grinding/HSM and EDM/HSM,” *CIRP Ann.*, vol. 50, no. 1, pp. 145–148, Jan. 2001, doi: 10.1016/S0007-8506(07)62091-5.

[14] B. Nau, A. Roderburg, and F. Klocke, “Ramp-up of hybrid manufacturing technologies,” *CIRP J. Manuf. Sci. Technol.*, vol. 4, no. 3, pp. 313–316, Jan. 2011, doi: 10.1016/J.CIRPJ.2011.04.003.

[15] J. R. Fessler, R. Merz, A. H. Nickel, F. B. Prinz, and L. E. Weiss, “Laser deposition of metals for shape deposition manufacturing,” *repositories.lib.utexas.edu*, Accessed: Jan. 03, 2022. [Online]. Available: https://repositories.lib.utexas.edu/handle/2152/69928.

[16] F. Klocke, H. Wirtz, W. M.-1996 International, and undefined 1996, “Direct manufacturing of metal prototypes and prototype tools,” *repositories.lib.utexas.edu*, Accessed: Jan. 03, 2022. [Online]. Available: https://repositories.lib.utexas.edu/handle/2152/69931.

[17] M. Kerschbaumer and G. Ernst, “Hybrid manufacturing process for rapid high performance tooling combining high speed milling and laser cladding,” *ICALEO 2004 - 23rd Int. Congr. Appl. Laser Electro-Optics, Congr. Proc.*, 2004, doi: 10.2351/1.5060234.

[18] A. Sreenathbabu, K. P. Karunakaran, and C. Amarnath, “Statistical process design for hybrid adaptive layer manufacturing,” *Rapid Prototyp. J.*, vol. 11, no. 4, pp. 235–248, 2005, doi: 10.1108/13552540510612929/FULL/HTML.

[19] Y. Song, S. Park, D. Choi, H. J.-I. J. of M. Tools, and undefined 2005, “3D welding and milling:

Part I–a direct approach for freeform fabrication of metallic prototypes," *Elsevier*, Accessed: Jan. 03, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0890695504003074.
[20] R. Kovacevic, 020,539 ME Valant - US Patent 7, and undefined 2006, "System and method for fabricating or repairing a part," *Google Patents*, 2006, Accessed: Jan. 03, 2022. [Online]. Available: https://patents.google.com/patent/US7020539B1/en.
[21] X. Xinhong, Z. Haiou, W. Guilan, W. G.-R. and Computer, and undefined 2010, "Hybrid plasma deposition and milling for an aeroengine double helix integral impeller made of superalloy," *Elsevier*, Accessed: Jan. 03, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0736584509000982.
[22] G. Manogharan, R. Wysk, O. Harrysson, R. A.-P. Manufacturing, and undefined 2015, "AIMS–a metal additive-hybrid manufacturing system: system architecture and attributes," *Elsevier*, Accessed: Jan. 03, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2351978915010215.
[23] D. G. Ahn, "Applications of laser assisted metal rapid tooling process to manufacture of molding & forming tools - state of the art," *Int. J. Precis. Eng. Manuf.*, vol. 12, no. 5, pp. 925–938, Oct. 2011, doi: 10.1007/S12541-011-0125-5.
[24] "5AXISMAKER." https://5axismaker.co.uk/ (accessed Jul. 05, 2022).
[25] "3D Printer/CNC/Laser Engraving - Creality 3D CP-01 - 200x200x200mm." https://grobotronics.com/3d-printer-cnc-laser-engraving-creality-3d-cp-01-200x200x200mm.html?sl=en (accessed Jul. 05, 2022).
[26] "CP-01 3D Printer - Creality 3D." https://www.creality.com/products/creality-cp-01-3d-printer (accessed Jul. 05, 2022).
[27] "da Vinci 1.0 Pro | 3D Printers | XYZprinting." https://www.xyzprinting.com/en-US/product/da-vinci-pro (accessed Jul. 06, 2022).
[28] "Review: Snapmaker 2.0 - 3-in-1 3D printer with CNC and laser capabilities - 3D Printing Industry." https://3dprintingindustry.com/news/review-snapmaker-2-0-3-in-1-3d-printer-with-cnc-and-laser-capabilities-192268/ (accessed Jul. 06, 2022).
[29] "SnapMaker 2.0 review | TechRadar." https://www.techradar.com/reviews/snapmaker-20 (accessed Jul. 06, 2022).
[30] "ZMorph VX Review: Best 3-in-1 3D Printer 2020 | All3DP Pro." https://all3dp.com/1/zmorph-vx-review-3d-printer-specs/ (accessed Jul. 06, 2022).
[31] "Home | Zmorph S.A." https://zmorph3d.com/ (accessed Jul. 06, 2022).
[32] S. Gamaralalage, P. Jesus, and D. Šormaz, "Conversion of the SCARA Robot into a Hybrid Manufacturing Workstation," in *Procedia Manufacturing*, 2018, vol. 17, pp. 62–69, doi: 10.1016/j.promfg.2018.10.013.
[33] A. N. M. Amanullah, Murshiduzzaman, T. Saleh, and R. Khan, "Design and Development of a Hybrid Machine Combining Rapid Prototyping and CNC Milling Operation," in *Procedia Engineering*, 2017, vol. 184, pp. 163–170, doi: 10.1016/j.proeng.2017.04.081.
[34] "Additive vs Subtractive Manufacturing: Difference | 3DE-Shop." https://www.3de-shop.com/post/additive-vs-subtractive-manufacturing-difference-pros-cons/.html (accessed Mar. 29, 2022).
[35] S. T. Zivanovic, M. D. Popovic, N. M. Vorkapic, M. D. Pjevic, and N. R. Slavkovic, "An overview of rapid prototyping technologies using subtractive, additive and formative processes," *FME Trans.*, vol. 48, no. 1, pp. 246–253, 2020, doi: 10.5937/fmet2001246Z.
[36] Z. Zhu, V. Dhokia, A. Nassehi, and S. T. Newman, "Investigation of part distortions as a result of hybrid manufacturing," *Robot. Comput. Integr. Manuf.*, vol. 37, pp. 23–32, Jul. 2016, doi: 10.1016/j.rcim.2015.06.001.
[37] "3D-Hybrid Introduces CNC-to-AM Adapter Tool to 3D Print Metal Parts » 3D Printing Media Network - The Pulse of the AM Industry." https://www.3dprintingmedia.network/3d-hybrid-introduces-cnc-arc-adapter-tool-3d-print-metal-parts/ (accessed Dec. 21, 2021).
[38] "Use Hybrid AM to Produce Longer-Lasting Multi-Material Molds | MoldMaking Technology." https://www.moldmakingtechnology.com/articles/use-hybrid-am-to-produce-longer-lasting-multi-material-molds- (accessed Dec. 21, 2021).
[39] "A multi-material part design framework in additive manufacturing | Request PDF." https://www.researchgate.net/publication/324786489_A_multi-

material_part_design_framework_in_additive_manufacturing (accessed Dec. 21, 2021).
[40] K. Hanson, *Machining For Dummies*. John Wiley & Sons, Inc, 2018.
[41] “3 Types of Manufacturing - Additive, Subtractive, and Forming.” https://www.techzone360.com/topics/techzone/articles/2019/09/09/443185-3-types-manufacturing-additive-subtractive-forming.htm (accessed Dec. 21, 2021).
[42] “Additive vs. Subtractive Manufacturing.” https://formlabs.com/blog/additive-manufacturing-vs-subtractive-manufacturing/ (accessed Dec. 21, 2021).
[43] “Additive Manufacturing vs Subtractive Manufacturing.” https://www.creativemechanisms.com/blog/additive-manufacturing-vs-subtractive-manufacturing (accessed Dec. 21, 2021).
[44] “What is Hybrid Manufacturing?” https://www.firetrace.com/fire-protection-blog/hybrid-manufacturing (accessed Dec. 21, 2021).
[45] L. Chen, K. Xu, and K. Tang, “Optimized sequence planning for multi-axis hybrid machining of complex geometries,” *Comput. Graph.*, vol. 70, pp. 176–187, 2018, doi: 10.1016/j.cag.2017.07.018.
[46] J. M. Flynn, A. Shokrani, S. T. Newman, and V. Dhokia, “Hybrid additive and subtractive machine tools - Research and industrial developments,” *Int. J. Mach. Tools Manuf.*, vol. 101, pp. 79–101, 2016, doi: 10.1016/j.ijmachtools.2015.11.007.
[47] M. F. Ashby, *Selection of Material and Shape*, Fourth Edi. Michael F. Ashby, 2011.
[48] “6061 T6 Aluminium Plate | ASTM B209 Sheet | T6 Coil / Foil Suppliers.” https://www.navstarsteel.com/6061-t6-aluminium-plate.html (accessed Dec. 21, 2021).
[49] “HG Series – Heavy Load Ball Type Linear Guideway On Hiwin Corporation.” https://motioncontrolsystems.hiwin.us/category/hg-series-heavy-load-ball-type-linear-guideway (accessed Dec. 21, 2021).
[50] L. Ball, B. Bearings, C. Shafting, and R. L. Guides, “RoundRail Linear Guides and Components Thomson – the Choice for Optimized Motion Solutions.”
[51] N. B. Corporation, “Basics of Linear Bearings | Nippon Bearing,” no. April, 2013, [Online]. Available: https://www.nbcorporation.com/basics-linear-bearings/.
[52] W. Dale, “Figure 1: Comparative strengths of different bearing types,” 2010.
[53] “Round Guide Rails VS Square Guide Rails for CNC Routers | STYLECNC.” https://www.stylecnc.com/user-manual/round-square-guide-rails-cnc-routers.html (accessed Apr. 05, 2022).
[54] “What is a linear motor – Principle - Magnets By HSMAG.” https://www.hsmagnets.com/blog/linear-motor-principle/ (accessed Dec. 26, 2021).
[55] “Servo Motor vs Stepper Motor.” https://www.omc-stepperonline.com/support-servo-motor/servo-motor-vs-stepper-motor (accessed Dec. 26, 2021).
[56] M. Automation, “Drives and Mechanisms Lecture 1 Elements of CNC machine tools: electric motors,” *NPTEL – Mech. – Mechatronics Manuf. Autom. Modul.*, pp. 1–47.
[57] M. Cortina, J. I. Arrizubieta, J. E. Ruiz, E. Ukar, and A. Lamikiz, “Study of the porosity generated by the use of cutting fluid in hybrid processes combining machining and Laser Metal Deposition (LMD),” in *Procedia CIRP*, 2018, vol. 74, pp. 733–737, doi: 10.1016/j.procir.2018.08.021.
[58] C. H. Yeung, Y. Altintas, and K. Erkorkmaz, “Virtual CNC system. Part I. System architecture,” *Int. J. Mach. Tools Manuf.*, vol. 46, no. 10, pp. 1107–1123, 2006, doi: 10.1016/j.ijmachtools.2005.08.002.
[59] M. Hanifzadegan, “Linear Parameter-Varying Control of Cnc Machine Tool Feed-Drives With Dynamic Variations,” *M.Sc. Amirkabir Univ. Technol.*, no. December, 2004.
[60] “Tutorial: Stepper vs Servo.” https://www.amci.com/industrial-automation-resources/plc-automation-tutorials/stepper-vs-servo/ (accessed Dec. 26, 2021).
[61] “Basics of Servo motor, it’s advantages and disadvantages - Electrical - Industrial Automation, PLC Programming, scada & Pid Control System.” https://forumautomation.com/t/basics-of-servo-motor-its-advantages-and-disadvantages/3186 (accessed Dec. 21, 2021).
[62] “Choosing a Stepper Motor Power Supply | Circuit Specialists.” https://www.circuitspecialists.com/blog/stepper-motor-power-supplies/ (accessed Dec. 26, 2021).
[63] “Stepper Motor - How Does a Stepper Motor Work? | Geckodrive.” https://www.geckodrive.com/support/step-motor-basics.html (accessed Dec. 26, 2021).
[64] F. Semiconductor and F. Ramirez, “Driving a Stepper Motor Based on the MC9S08QD4 and

Other 8-bit Families," vol. 8, 2008.
[65] "Stepper motor torque and speed characteristics explained." https://www.linearmotiontips.com/stepper-motor-torque-speed-characteristics-explained/ (accessed Dec. 26, 2021).
[66] "Comparing Ball Screw VS Acme Screw – Progressive Automations." https://www.progressiveautomations.com/blogs/how-to/acme-screw-ball-screw (accessed Dec. 21, 2021).
[67] J. Carvill, "Applied mechanics," *Mech. Eng. Data Handb.*, pp. 57–101, 1993, doi: 10.1016/B978-0-08-051135-1.50007-8.
[68] P. R. N. Childs, "Fastening and Power Screws," *Mech. Des.*, pp. 371–412, 2021, doi: 10.1016/B978-0-12-821102-1.00010-X.
[69] P. G. Adamczyk, "Semi-active prostheses for low-power gait adaptation," *Powered Prostheses*, pp. 201–259, 2020, doi: 10.1016/B978-0-12-817450-0.00009-2.
[70] P. Moubarak and P. Ben-Tzvi, "Modular and reconfigurable mobile robotics," *Rob. Auton. Syst.*, vol. 60, no. 12, pp. 1648–1663, 2012, doi: 10.1016/J.ROBOT.2012.09.002.
[71] "Power Screws - Roy Mech." https://roymech.org/Useful_Tables/Cams_Springs/Power_Screws.html (accessed Dec. 21, 2021).
[72] "China High Quality Hollow Rotary Table Manufacturers, Suppliers, Factory - SAINI." https://www.gigager.net/hollow-rotary-actuator/hollow-rotary-table.html (accessed Dec. 26, 2021).
[73] JVL, "Hollow Rotary Actuators, HLMT," pp. 1–9, 2021.
[74] H. R. Table, "G + SV Type for Servo Motor G + Revolutionary New Solution for Rotary Motion Control."
[75] E. Turkes, S. Orak, S. Neseli, and S. Yaldiz, "Linear analysis of chatter vibration and stability for orthogonal cutting in turning," *Int. J. Refract. Met. Hard Mater.*, vol. 29, no. 2, pp. 163–169, 2011, doi: 10.1016/j.ijrmhm.2010.10.002.
[76] E. Turkes, S. Orak, S. Neseli, and S. Yaldiz, "A new process damping model for chatter vibration," *Meas. J. Int. Meas. Confed.*, vol. 44, no. 8, pp. 1342–1348, 2011, doi: 10.1016/j.measurement.2011.04.004.
[77] E. Turkes, S. Orak, S. Neseli, and S. Yaldiz, "Decomposition of process damping ratios and verification of process damping model for chatter vibration," *Meas. J. Int. Meas. Confed.*, vol. 45, no. 6, pp. 1380–1386, 2012, doi: 10.1016/j.measurement.2012.03.028.
[78] Vrtiel, Hajdu, and M. Behúlová, "Analysis of the machine frame stiffness using numerical simulation," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 266, no. 1, 2017, doi: 10.1088/1757-899X/266/1/012015.
[79] A. Max, M. Hynek, and L. Řehounek, "ENGINEERING MECHANICS 2016 DYNAMIC ANALYSIS OF CNC MILLING MACHINE FRAME," no. May, pp. 9–12, 2016.
[80] Z. Zhou, D. Chen, and S. (Shengquan) Xie, *Springer Series in Advanced Manufacturing*. 2007.
[81] L. Sai, R. Belguith, M. Baili, G. Dessein, and W. Bouzid, "An approach to modeling the chip thickness and cutter workpiece engagement region in 3 and 5 axis ball end milling," *J. Manuf. Process.*, vol. 34, pp. 7–17, 2018, doi: 10.1016/j.jmapro.2018.05.018.
[82] S. Mandrile, G. Cazenave-Larroche, C. Vernault, G. Dessein, J. Denape, and J. Y. Paris, "Development of an in-house cutting forces simulation for fir tree broaching process," *Int. J. Mach. Mach. Mater.*, vol. 15, no. 1–2, pp. 18–35, 2014, doi: 10.1504/IJMMM.2014.059185.
[83] G. M. Martinov, A. I. Obuhov, L. I. Martinova, and A. S. Grigoriev, "An approach to building specialized CNC systems for non-traditional processes," in *Procedia CIRP*, 2014, vol. 14, pp. 511–516, doi: 10.1016/j.procir.2014.03.049.
[84] E. D. Weflen, M. C. Frank, and P. Collins, "A hybrid additive and subtractive manufacturing approach for multi-material components," 2020.
[85] A. N. M. Amanullah, Murshiduzzaman, T. Saleh, and R. Khan, "Design and Development of a Hybrid Machine Combining Rapid Prototyping and CNC Milling Operation," *Procedia Eng.*, vol. 184, pp. 163–170, 2017, doi: 10.1016/j.proeng.2017.04.081.
[86] W. Grzesik, "Hybrid additive and subtractive manufacturing processes and systems: A review," *J. Mach. Eng.*, vol. 18, no. 4, pp. 5–24, 2018, doi: 10.5604/01.3001.0012.7629.
[87] "| Fabrisonic." https://fabrisonic.com/top-five-reasons-use-hybrid-additive-manufacturing-machines-vs-single-focus-special-machines-running-parallel/ (accessed Mar. 20, 2022).

[88] [Online]. Available: https://www.bcn3d.com/introduction-fff-3d-printing-technology-additive-manufacturing-basics/. BCN3D Technologies[1] BCN3D Technologies, “Introduction to Fused Filament Fabrication (FFF) 3D printing technology,” pp. 1–15, 2019, “Introduction to Fused Filament Fabrication (FFF) 3D printing technology,” pp. 1–15, 2019, [Online]. Available: https://www.bcn3d.com/introduction-fff-3d-printing-technology-additive-manufacturing-basics/.
[89] S. Singh, G. Singh, C. Prakash, and S. Ramakrishna, “Current status and future directions of fused filament fabrication,” *J. Manuf. Process.*, vol. 55, no. December, pp. 288–306, 2020, doi: 10.1016/j.jmapro.2020.04.049.
[90] B. Brenken, E. Barocio, A. Favaloro, V. Kunc, and R. B. Pipes, “Fused filament fabrication of fiber-reinforced polymers: A review,” *Addit. Manuf.*, vol. 21, pp. 1–16, 2018, doi: 10.1016/j.addma.2018.01.002.
[91] H. C. Song, N. Ray, D. Sokolov, and S. Lefebvre, “Anti-aliasing for fused filament deposition,” *CAD Comput. Aided Des.*, vol. 89, pp. 25–34, 2017, doi: 10.1016/j.cad.2017.04.001.
[92] M. A. Matos, A. M. A. C. Rocha, and A. I. Pereira, “Improving additive manufacturing performance by build orientation optimization,” *Int. J. Adv. Manuf. Technol.*, vol. 107, no. 5–6, pp. 1993–2005, 2020, doi: 10.1007/s00170-020-04942-6.
[93] D. Syrlybayev, B. Zharylkassyn, A. Seisekulova, M. Akhmetov, A. Perveen, and D. Talamona, “Optimisation of strength properties of FDM printed parts—A critical review,” *Polymers (Basel).*, vol. 13, no. 10, 2021, doi: 10.3390/polym13101587.
[94] E. Zaneldin, W. Ahmed, A. Mansour, and A. El Hassan, “Dimensional stability of 3d printed objects made from plastic waste using fdm: Potential construction applications,” *Buildings*, vol. 11, no. 11, 2021, doi: 10.3390/buildings11110516.
[95] M. Ziółkowski and T. Dyl, “Possible applications of additive manufacturing technologies in shipbuilding: A review,” *Machines*, vol. 8, no. 4, pp. 1–34, 2020, doi: 10.3390/machines8040084.
[96] H. Quinlan, A. P. Technologies, A. J. Hart, D. Advanced, and P. Technologies, “Additive Manufacturing : Implications for Technological Change , Workforce Development , and the Product Lifecycle,” no. November, 2020.
[97] C. U. Brown *et al.*, “The Effects of Laser Powder Bed Fusion Process Parameters on Material Hardness and Density for Nickel Alloy 625,” *NIST Adv. Manuf. Ser.*, pp. 100–119, 2018, [Online]. Available: https://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.100-19.pdf%0Ahttps://doi.org/10.6028/NIST.AMS.100-19%0Ahttps://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.100-19.pdf.
[98] J. Jones and P. Coates, “7 Families of Additive Manufacturing (ASTM F2792),” *Www.Hybridmanutech.Com*, pp. 1–2, 2015, [Online]. Available: https://www.additivemanufacturing.media/cdn/cms/7_families_print_version.pdf.
[99] M. L. Vlasea, B. Lane, F. Lopez, S. Mekhontsec, and A. Donmez, “Test Bed for Enhanced Real-Time Process Control,” *Natl. Inst. Stand. Technol.*, pp. 527–539, 2015.
[100] “Aeromet and Partners Continue Development of A20X Aluminum Alloy for 3D Printing - 3DPrint.com | The Voice of 3D Printing / Additive Manufacturing.” https://3dprint.com/210009/aeromet-partners-a20x-alloy/ (accessed Mar. 25, 2022).
[101] “Rapid Prototyping.” https://www.aeromet.co.uk/capabilities/rapid-prototyping#rapid3 (accessed Mar. 26, 2022).
[102] D. E. Mouzakis, “Advanced Technologies in Manufacturing 3D-Layered Structures for Defense and Aerospace,” *Lamination - Theory Appl.*, 2018, doi: 10.5772/intechopen.74331.
[103] DMG Mori, “All in 1: Laser Deposition Welding & Milling -additive Manufacturing in Milling quality,” pp. 1–12, 2014, [Online]. Available: http://us.dmgmori.com/products/lasertec/lasertec-additivemanufacturing/lasertec-65-3d#Intro.
[104] T. Right, “Pl0Us-Additive-Manufacturing-Pdf-Data.Pdf,” [Online]. Available: https://en.dmgmori.com/products/machines/additive-manufacturing/powder-nozzle/lasertec-65-ded-hybrid%0Ahttps://en.dmgmori.com/resource/blob/71066/db7d4d589d66c2838c9570d4eee3ac03/pl0uk-additive-manufacturing-pdf-data.pdf.
[105] A. Elser, M. Königs, A. Verl, and M. Servos, “On achieving accuracy and efficiency in Additive Manufacturing: Requirements on a hybrid CAM system,” in *Procedia CIRP*, 2018, vol. 72, pp. 1512–1517, doi: 10.1016/j.procir.2018.03.265.
[106] K. A. Lorenz, J. B. Jones, D. I. Wimpenny, and M. R. Jackson, “A review of hybrid

manufacturing," *Proc. - 26th Annu. Int. Solid Free. Fabr. Symp. - An Addit. Manuf. Conf. SFF 2015*, pp. 96–108, 2020.
[107] I. Gibson, D. Rosen, and B. Stucker, *3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*. 2015.
[108] S. Ford and M. Despeisse, "Additive manufacturing and sustainability: an exploratory study of the advantages and challenges," *J. Clean. Prod.*, vol. 137, pp. 1573–1587, 2016, doi: 10.1016/j.jclepro.2016.04.150.
[109] T. Tunç, Ö. Özkırımlı, and E. Öztürk, "Machining strategy development in 5-axis milling operations using process models," *Proc. 4th CIRP Int. Conf. High Perform. Cut.*, 2010, [Online]. Available: http://research.sabanciuniv.edu/15601/.
[110] M. Heino, I. Oy, and J. Vaasko, "AUTOMATIC TOOL CHANGING SYSTEM FOR MHI3D PRINTER Subject Automatic tool changing system for MHI3D printer," 2019.
[111] P. Czyżewski, D. Marciniak, B. Nowinka, M. Borowiak, and M. Bieliński, "Influence of Extruder's Nozzle Diameter on the Improvement of Functional Properties of 3D-Printed PLA Products," *Polymers (Basel).*, vol. 14, no. 2, 2022, doi: 10.3390/polym14020356.
[112] J. Zhao, "Design of 3D metal FDM printing nozzle based on melt forming," *Chem. Eng. Trans.*, vol. 59, pp. 73–78, 2017, doi: 10.3303/CET1759013.
[113] C. Li, W. Cheng, and J. Hu, "Nozzle Problem Analysis and Optimization of FDM 3D Printer," *Proc. 2017 7th Int. Conf. Mechatronics, Comput. Educ. Informationization (MCEI 2017)*, vol. 75, no. Mcei, pp. 270–273, 2018, doi: 10.2991/mcei-17.2017.59.
[114] Y. Tlegenov, G. S. Hong, and W. F. Lu, "Nozzle condition monitoring in 3D printing," *Robot. Comput. Integr. Manuf.*, vol. 54, no. December 2018, pp. 45–55, 2018, doi: 10.1016/j.rcim.2018.05.010.
[115] R. Ingman, "Adaption of a Heatsink To Additive Manufacturing," p. 70, 2019.
[116] "What is a Heat Sink - Sunpower UK." https://www.sunpower-uk.com/glossary/what-is-a-heat-sink/ (accessed Mar. 21, 2022).
[117] T. Tichý, O. Šefl, P. Veselý, K. Dušek, and D. Bušek, "Mathematical modelling of temperature distribution in selected parts of fff printer during 3d printing process," *Polymers (Basel).*, vol. 13, no. 23, pp. 1–10, 2021, doi: 10.3390/polym13234213.
[118] R. Smith, C. Technologist, and W. Jordan, "THERMAL TESTING OF A 3D PRINTED NON-UNIFORM HEATSINK AGAINST STATE-OF- THE-ART FINNED GEOMETRY 6764 Airport Road," 2015.
[119] J. Yaple, D. Bhate, B. Azeredo, and P. Phelan, "Design and Additive Manufacturing of Copper Heat Sinks for Microelectronics Cooling," no. August, 2021.
[120] BCN3D, "The anatomy of an Extrusion System," pp. 1–17, 2019.
[121] T. Faculty, "Thermal analysis of a 3d printer hotend and nozzle," pp. 1368–1375.
[122] G. Gutiérrez Arias, F. Jiménez Díaz, E. Rúa Ramírez, and J. Valcarcel Guzman, "Thermal Analysis by Finite Elements of Hotends for 3D Printing by Fused Filament Fabrication," *Period. Polytech. Mech. Eng.*, vol. 65, no. 2, pp. 129–133, 2021, doi: 10.3311/ppme.16203.
[123] M. A. Hossain *et al.*, "Low-Cost 3D Printer Drawn Optical Microfibers for Smartphone Colorimetric Detection," *Biosensors*, vol. 12, no. 2, pp. 1–10, 2022, doi: 10.3390/bios12020054.
[124] D. Lawrence Berkeley National Laboratory Washington, "Improving Fan System Performance: A Sourcebook for Industry," *U.S. Dep. Energy*, p. 83, 2003.
[125] M. Briscoe and G. Aglietti, "Spacecraft Mechanisms," *Spacecr. Syst. Eng.*, pp. 520–523, 2003.
[126] "Slip ring - Wikipedia." https://en.wikipedia.org/wiki/Slip_ring (accessed Mar. 22, 2022).
[127] G. Dorsey, "Video Signals and Slip Rings," pp. 1–8.
[128] "Calculating CNC Machining Cost: Know All Factors and Tips | RapidDirect." https://www.rapiddirect.com/blog/cnc-machining-cost-calculation/ (accessed Mar. 23, 2022).
[129] "Weerg | CNC and 3D Printing Online - Instant Online Quote." https://www.weerg.com/en/global/hmpg?utm_campaign=ADW+WRD+all+keywords+Sales-Search-656+dsk+ROAS&utm_medium=ppc&utm_source=adwords&utm_term=3d printing price&hsa_mt=p&hsa_net=adwords&hsa_ad=555922099140&hsa_src=g&hsa_cam=15069524821&hsa_kw=3d printing price&hsa_grp=131875249827&hsa_tgt=kwd-11041673982&hsa_ver=3&hsa_acc=5333437716&gclid=CjwKCAjwiuuRBhBvEiwAFXKaNHMaSrZ_7sGncYcYn098oYkl3T0yspJ1wS8waMjBcS-7lEZJY7opOxoCakcQAvD_BwE (accessed Mar. 24, 2022).

Material extrusion 3D printing system for hybrid CNC machines with automatically changed standard tool holders

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Abstract

Additive Manufacturing is a transformational approach to industrial production that allows the creation of lightweight components of complicated geometry, which could not be manufactured with traditional production processes. The need to save time and costs plays a key role in the development of any industrial unit. However, the surface quality and production time of the 3D printed parts make it impossible to apply the method for industrial applications. In this direction, in the last two decades, the machine tool industry has started to develop manufacturing hybrid machine tools. These combine the operation of CNC machining centers with 3D printers. This study proposes a new design of a head extrusion 3D printer with the aim of creating an innovative automatic tool replacement system for hybrid machine tools. This way, material extrusion heads can automatically be interchanged or be changed with cutting tools, so that hybrid manufacturing tools can be utilized easily and quickly without the intervention of the operator.

Keywords: 3D printing, CNC machining, Additive Manufacturing, Subtractive Manufacturing, material extrusion, tool holders

1. Introduction

The term Hybrid Manufacturing (HM) has been used to describe the combination of conventional and non-conventional machining processes in a single work environment: a single machine or a closed manufacturing cell. Thus, Hybrid Machine Tools (HMT), which perform HM, integrate different machining functions into one machine. Recently, this term has mainly been affiliated with the combination of Additive Manufacturing (AM) and Subtractive Manufacturing (SM) processes, which run on a single machine in series or in parallel (([1],[2],[3],[4],[5]). Commonly, HMT are either multifunctional CNC machine tools which include an AM unit for building a rough original part or 3D printers that incorporate a spindle and cutting tools for fine detailing (engraving and/or surface finishing) the 3D printed part. In the same direction, robotic systems have also been utilized, as they can inherently operate with various and interchangeable end-effectors with regard to the task they need to perform. As a result of the HM philosophy, the manufacture of a part though iterative material adding and subtracting is carried out on a machine without additional set-ups, fastening and transferring from one machine to another to complete it. This has a number of benefits, such as minimizing set-up and down-times, cost and material usage, and maximizing part quality, process repeatability and productivity. The main reasons for the use of HMT in productions of parts of high surface quality and high geometric complexity in low production volumes ([6],[7],[8],[9]) are:

- Repairing. HMTs allow the use of both material addition (cladding) and removal to repair existing high-added value components, such as compressors and turbines.
- Surface Finishing. Introducing material removal procedures to additively produced parts to finish interior and exterior component features and surfaces.
- Precision. Hybrid system technology allows 3D printing and surface finishing in the same reference coordinate system, allowing for critical tolerances.
- Complexity. Due to the involvement of AM processes, hybrid machine tools offer the ability to build very intricate/complex part geometries and are greatly flexible in their manufacture.
- Multi-material part production. Components consisting of different materials are even difficult to produce with the use of AM alone. A hybrid system allows the build process to start with 3D printing of one material, followed by SM stages for proper surface preparation, then continuing with other 3D printing stages of the same or different materials, so as to make multi-materials parts whose different material are properly joined together.

In general, AM uses powder or wire/filament as initial raw material for deposition, in order to make components almost identical in shape to the designed models. Typically, powder technology is adopted for relatively small and thin components, while wire/filament technology is recommended for larger structural components, as the material addition rate is higher in the latter. However, CNC finishing operations can be applied to ensure the desired accuracy by eliminating the stair-step effects resulting from the layer-by-layer deposition. It is well known that the manufacturing with layer-by-layer deposition method is at least one order of magnitude slower than the subtractive process with CNC for achieving the same theoretical surface finish ([10],[11],[12]). The technological dilemma is whether to choose higher productivity AM process with thicker deposition layers, but lower surface finish due to “staircase effect”, or higher surface quality by performing a slower deposition of thinner layers, thus sacrificing process productivity ([13],[14],[15]). In other words, AM process productivity can be increased with greater energy input, yielding thicker layers of material and faster process, but this way the part’s surface finish deteriorates. Conversely, using the slower approach, with deposition of layers of smaller heights, the creation of a better surface finish can be achieved, but at higher costs when high part accuracy is needed.

Over the last two decades, during which AM has significantly advanced and has managed to provide high accuracies similar to the ones achieved by SM processes, there is serious debate and competition between the two approaches. Both approaches have their benefits and their drawbacks. In short, SM offers high surface quality and high part integrity at low processing costs and high productivity, but it suffers from low material buy-to-fly ratio, as the machining commonly starts with a primitive geometry raw part (cylindrical or prismatic) equal to or larger than the final part envelop, high tooling, consumables and setup costs and energy consumption. On the other hand, AM processes demonstrate high material usage efficiency, low tooling and consumables costs, multi-material parts, and the ability to create very intricate and complex internal and external part morphologies, but they result in relatively low surface quality parts at acceptable productivity rates, raw material (powder and wire/filament) at higher costs because of the extra production stages, low repeatability, questionable structural integrity, and the need for post-processing (thermal, UV or pressure) before AM products can be utilized.

Rather than considering AM and SM competitive to each other, the Hybrid Manufacturing approach engulfs them both as complementary technologies. It is the technological bridge that allows material to be printed, material added to existing components, low mass components to be developed with high complexity, and then allows machining for improving dimensional and operational accuracy on the same machine tool. Thus, the hybrid technology incorporates AM and SM operations in a multi-stage profitable process for small and medium batches, due to the fact that productivity and surface finish can be controlled independently. In other words, if high-quality AM parts must be produced at acceptable production cost, the optimal strategy has proven to be the rough deposition of material complimented with fine CNC machining intermediate and final finishing stages.

The combination of additive and subtractive processes, whether on different or ideally on the same machine, is currently an almost established practice for the vast majority of parts produced by AM, which require additional machining in order to achieve a suitable surface finish, tighter tolerances, functional properties and avoid excessive residual stresses. It also results in a significant reduction in material and energy wastage, due to the fact that controlled material deposition is used instead of solid raw stock material ([16],[17],[18]).

The aim of this work is the development of an innovative design for material extrusion 3D printing mechanism that fits directly in standard tool holders and electrically connects via slip-rings, so that no other electrical cables and connections are required. This innovation helps minimize components and simplifies the overall construction of a HMT, which makes parts from polymer, elastomer and special type composite materials, e.g., non-fabric type short or long carbon fiber reinforced polymers, of increased complexity. The proposed mechanism's layout allows the automated change of filament extrusion nozzles, so that it can be replaced quickly and easily at any time, as is the case with the ATC of typical CNC milling machines. The system must be located inside the HMT and a number of hot-end units can be selected, as required by the process plan. Although it does not fall within the scope of this study, the operation of the automatic tool change system is briefly discussed, as this requires proper definition of G-code commands and its low-level programming in the CNC machine tool controller.

2. State of the art

One of the main problems that arises when combining AM and SM technologies in a machine is the installation of the AM unit in a CNC machine tool without special modifications. Multi-axis CNC milling centers are typically the machine tool basis upon which the AM unit is to be installed. Most research efforts focus on designing a modular hybrid platform that incorporates various AM with SM. Existing commercial HM systems can be divided into two main categories: (a) HM for metallic parts and (b) HM for polymeric parts, mainly thermoplastics.

The HM for metallic parts can be further divided into three subcategories:

(i) Directed Energy Deposition for AM and 3- to 5-axis CNC milling for SM processes (such as DMG Mori laser 3D 65 & 4300, MAZAK Integrex i-400AM, VC-500 AM & Variaxis j-600AM, Laser EX & MULTUS U laser EX and HERMLE C-400) [7],
(ii) Powder Bed Fusion for AM and 3-axis CNC milling for SM processes (such as Sodick OPM250L & OPM350L and Matsuura Lumex Avance 25 & 60), [19]
(iii) Laminated Object Manufacturing (ultrasonic solid-state welding) for AM and 3- to 5-axis CNC milling for SM processes (Fabrisonic SonicLayer 7200), [20], [21]

The HM for polymeric parts combines Fused Deposition Modelling (FDM), CNC milling and/or laser engraving/cutting technologies. Examples of commercially available HMTs are Creality CP-01, daVinci 1.0 Pro 3-in-1, Dobot Mooz 2 Plus, Diabase Engineering H-series, Snapmaker 2.0 Modular 3-in-1, ZMorph VX, 5axismaker 5xm series.

One for the first HMTs was developed by AeroMet Corp. ([22], [23]), which incorporates a laser source for depositing material on a CNC milling machine to produce metallic products for the aerospace industry, specifically for the F-15 Fighters, in 2004. This system is not as efficient due to technical problems with the CO_2 laser and the powder supply [24].

A design problem for HMT manufacturers is the way in which the AM module will be connected to the basic structure of the machine. DMG Mori [25] adapted the laser deposition unit to fit to HSK63 tool holders to control the movement of the AM head on the Z axis of the machine tool. The AM head (Laser Deposition Welding, LDW), however, should be stored outside the work area of the CNC machine tool after each deposition operation, when it was replaced by the cutting tools. Moreover, the workpiece should be electrically grounded when depositing the welded material ([26],[27]).

Most AM units from the first category are dedicated to the machines they are fitted to. However, a couple of companies have created AM units that can be fitted into standard CNC machine tool holders. Thus, the Ambit system of Hybrid Manufacturing Technologies company offers a number of different deposition heads, both for metals and polymers, which are fully compatible with a standard tool changer and any standard CNC machine tool spindle (CAT 40, HSK36, etc.). The heads are automatically connected to a power supply and shielding gas, where needed. Another similar approach is introduced by 3D hybrid company. In general, laser deposition heads can have different geometries and material delivery configurations ([28],[29],[20],[30]). Thus, a CNC must be mildly or intensely retrofitted in order to accommodate for all primary and secondary subsystems for the AM unit to work as intended.

The idea of integrating FDM with CNC milling operations and/or laser engraving/cutting is recently evolved through the need of producing high quality polymeric parts, as described in category (b), driven by amateur and professional makers to have an all-in-one system for both prototyping and production purposes. The systems mentioned above, mainly incorporate 3-axis operations, with the exception of 5axismaker and Diabase Engineering ones, that allow multi-axis production. Moreover, only the latter is equipped with an ATC for the cutting tools, which is a separate unit from the AM one.

The designed material extrusion mechanism is fitted in standard tool holders of a compact 5-axis table-top CNC machine tool, thus formulating a HMT for polymer-based materials. Its main application is the printing of polymer components or polymer matrix fiber reinforced components, that demonstrate increased mechanical strength, without additional support [109]. After producing slightly oversized parts by material extrusion, CNC milling operations iteratively finish the part. In this way, a low-cost AM method is implemented, but part distortion caused by thermal residual stresses and the inherent low repeatability of material extrusion is overcome by the precise CNC cutting operations. The main innovation in the design of the proposed system is the way electricity is transferred to the extruder through a slip ring, thus allowing for easier automatic tool changes without fixed cable connections.

3. Design of the material extrusion system

The AM unit of a typical material extrusion 3D printer includes a nozzle, a heater, a heat sensor and a heating block (see Figure 1). In order to replace the nozzle, the user needs tools to disassemble the hot-end unit, which is time-consuming. Therefore, in order to facilitate HMT operations, the process of changing the nozzle or AM unit must be automated. This is achieved by developing an automated tool changer (ATC) for the machine tool, thus defining an automatic replacement process, designing and realizing an automatic nozzle change mechanism.

Generally, mechanical design is the process of creating a system, part or process to meet the desired needs and specifications. It is a decision-making process, in which the sciences of engineering and mathematics are applied for the optimal conversion of resources to achieve a specific aim. Product design research was conducted, and the following issues were considered:

1. Safety
2. Manufacturing and assembly
3. Cost
4. Quality
5. Portability

During the design process the necessary aspects were evaluated, such as functionality, technical characteristics, cost analysis and timing. Thus, the material extrusion and ATC system was designed, according to the requirements of a 5-axis hybrid machine (Table 1).

Table 1. Design Specifications for the proposed material extruder and ATC [32]

Aspects	**Specifications**
Size	The size of the systems must be kept as small as possible, so that it is lightweight, and the possibility of collision during multi-axis movements is minimized.
Functionality	The basic operation requirement is that the extruder should operate automatically, according to the given G-code program.
Manufacturing	Manufacturing and assembly must be simple, easy, efficient and error-free.
Cost	Low cost with good operational performance.

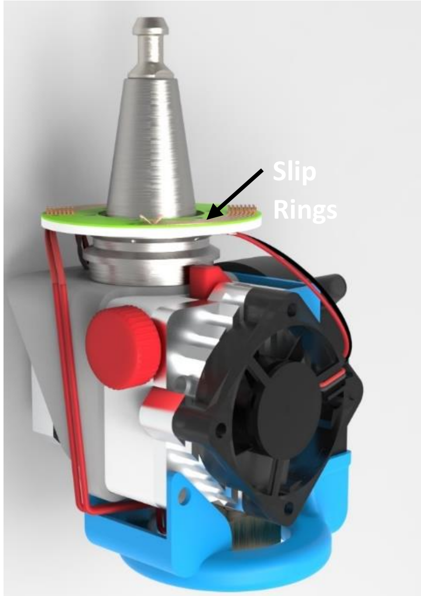

Figure 1. The proposed material extrusion system.

The material extrusion mechanism design is a part of the research carried out for an overall HMT design study, as presented in "Design and analysis of a desktop multi-axis hybrid milling-filament extrusion CNC machine tool for non-metallic materials". The proposed mechanism can be placed on any standard tool holder (eg. ER16, BT40) The following sections analyze the parts that make up the extruder system.

3.1 Nozzle

Nozzle is a part of the 3D printer that extrudes the filament to create the printed features, it has a great impact on the printing time as well as on print quality of a part. The larger the nozzle, the more mass and surface area of the nozzle is available to transfer heat to the filament, making this process more efficient and capable of higher extrusion speeds. The thermal conductivity of the nozzle is also related to its material, as each material transfers energy differently based on its properties. The inner diameter of the nozzle affects the amount of material that is extruded, which also determines the maximum extrusion speed. This also affects the accuracy of the 3D printed part. Smaller diameters allow thinner layers and walls to be printed. These three nozzle characteristics can have a big impact on the build time and the quality of the finished parts. Usually, a compromise must be reached between these two objectives. Nozzles are made of metal material, due to the relatively high thermal conductivity and the strict tolerances of its construction. A number of metals are used in the construction of nozzles. Each has unique properties, which affect the process of 3D printing in different ways ([33],[34],[35],[36]).

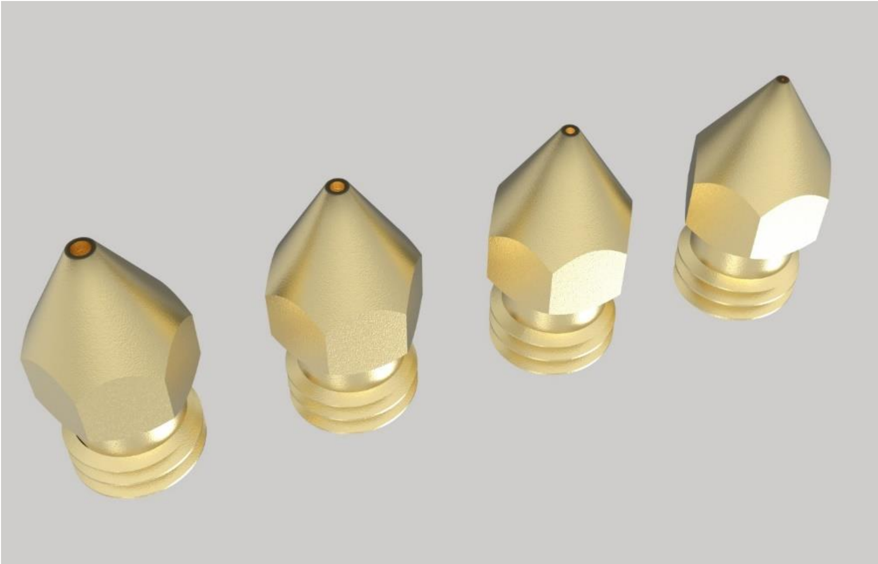

Figure 2: 3D nozzle designs for different nozzle diameters

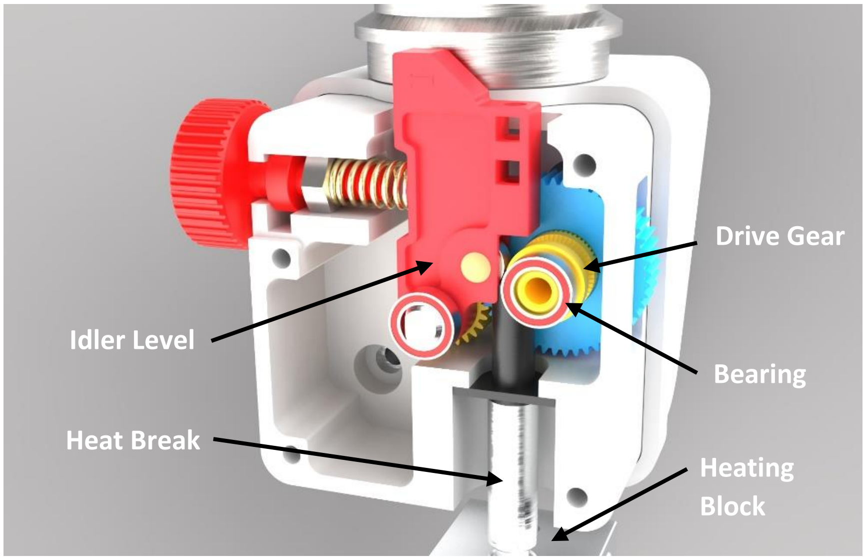

Figure 3: Section material extrusion systems

3.2 Heatsink

Heatsinks (Fig. 4) are critical components in the extruder assembly, as they help manage the heat transfer and keep components in specific temperatures. Heat transfer capacity has been widely researched in the design of a heatsink. There are two typical types of heatsinks, namely the passive and the active ones. Active heatsinks use cooling fans or blowers. Heat transfer using liquid cooling has two main disadvantages: (a) increased weight, and (b) possible coolant leakage results in short circuits in the electronics. In addition, there is also the issue of increased corrosion with water-based coolants ([37],[38]). The heatsink is the area where the heated filament comes through and into the nozzle and moves along the printing bed to create 3D parts. Because the filament needs to be heated up and partially liquify, the heatsink reaches 300°C and thus must be insulated from the rest of the printer. Different filament materials demand different temperatures for optimal 3D printing. These temperatures can be adjusted by the hybrid machine tool control software [39], [40], [41].

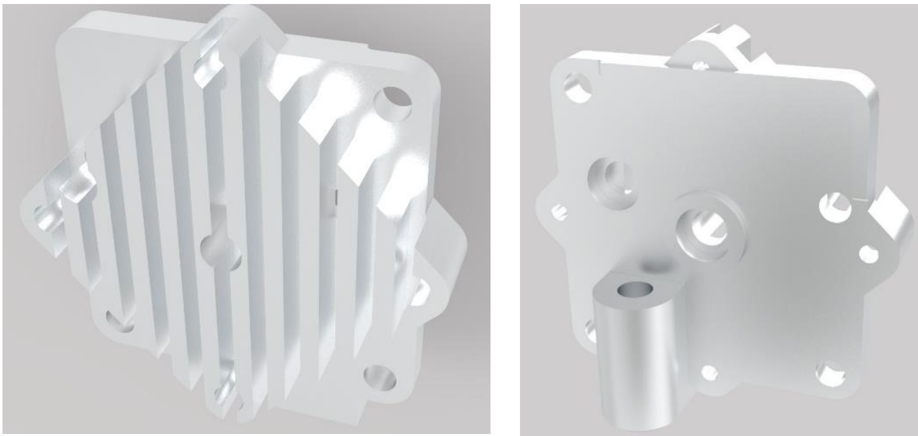

Figure 4: Heatsink 3D model

3.3 Heating block

The thermal element or heating block in an extrusion-type 3D printer is the part of the extruder where the nozzle meets the heat pipe and generally is a simple rectangular solid heat-conducting metallic part. This also encloses the thermistor, which measures temperatures inside the heat block for temperature control reasons. Usually made of aluminum, this component literally acts as a heat block, melting the filament as it passes through the heat pipe to be extruded from the nozzle ([42],[43],[44]).

3.4 Cooling Fan

Extruded 3D parts can be cooled by gases, liquids or by contact with a heat absorbing surface. Generally, profiles, pipes and cable housing are water cooled, other types of extruders are air cooled. Air cooling was chosen for the proposed design, owing to its simplicity and the minimal usage of components. Cooling fans are components included in all types of 3D printers. Fans used in this project are brushless ones, containing two terminals for direct current power supply. These have quiet operation and a long life. They are ideal for cooling 3D printer hot-ends ([45], [46]).

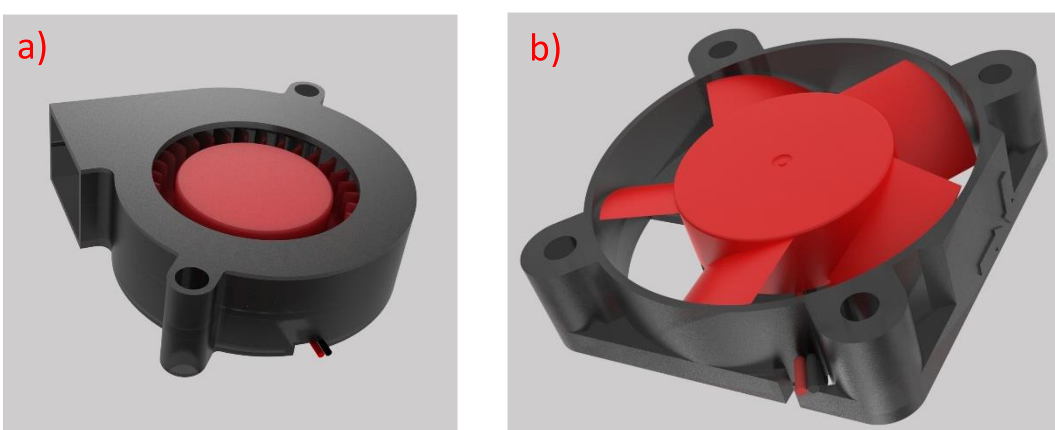

Figure 5: a) Radial Cooling Fan, b) Axial Cooling Fan, used in extrusion-type 3D printers

3.5 Drive Gear

Drive (extruder) gear is a gear in the extruder assembly that grips the filament and makes it move towards or away from the nozzle. It is capable of high torque without damaging the filament and adapts directly to the stepper motor shaft, making it easy to install, but effective in constant extrusion.

3.6 Heat Break

Heat break is connected to the heat sink and heat block, which controls most of the heat near the nozzle, creating as small a transition area as possible.

3.7 Idler Level

Idler level is a part of the mechanism that adapts the filament to the hot-end. It is connected using a spring on it that makes the lever flexible to ush. The bearing is mounted on a lever that rotates continuously to push the filament through the heated components. The coupling plate and the level are assembled using screws.

3.8 Slip Rings

A slip ring is a rotating conductive device with a mid-hole structure (Figure 1). Sliding rings around axles and axial components have been used to transmit precision signals, weak currents, high currents, high voltages, etc. These rings are designed for mechanisms with enough space allowance in the axial direction while in the radial direction there is limited space to fit and install. Slip rings are perfect for providing ultra-compact connection in such cases. Slip rings can be used in any electromechanical system that requires unlimited, continuous rotation during the transfer of power or data from a fixed to a rotating structure. Its electromechanical properties can simplify the system design and eliminate possible damage during rotation. It is essential for precision rotary worktables, electrical instruments, processing machines and control instruments. Its use in the proposed mechanism is to supply power and to transfer signals to the hot-end, avoiding use of cables, thus resulting in the simplification of the automatic tool change system ([47], [48],[49]).

4. Extruder mechanism manufacturing

System components were mainly made using CNC milling and 3D printing, while some were commercially available and thus sourced. Table 2 shows the Bill of Materials for the mechanism, along with the way that they were obtained and the respective estimated production time when custom built.

Table 2: Bill of Materials Manufacturing time process and material

	Part	Material	Manufacturing Process/ Commercially Available	Estimated production time (min)
1	Nozzle	Brass	Commercially available	-
2	Heating Block	Stainless steel		
3	Filament Drive Gear			
4	Heating Break			
5	Tool Holder ER 16			
6	Ceramic cartridge heater	Ceramic		
7	Slip Ring Connector	ABS Plastic		
8	Heatsink	Aluminum	Milling	65
9	Cover			40
10	Frame			70
11	Drive Gear Extruder	Polycarbonate	3d Printing	26
12	Idler Level			30
13	Cooler Fan Duct			305
14	Thumb Screw			31
15	Motor Drive Gear			10

Production time for CNC machining was calculated using CAM software, while a commonly used slicer was used to calculate printing time of the 3D printed parts (the strategy selection process for the optimal machining process is beyond the scope of this paper).

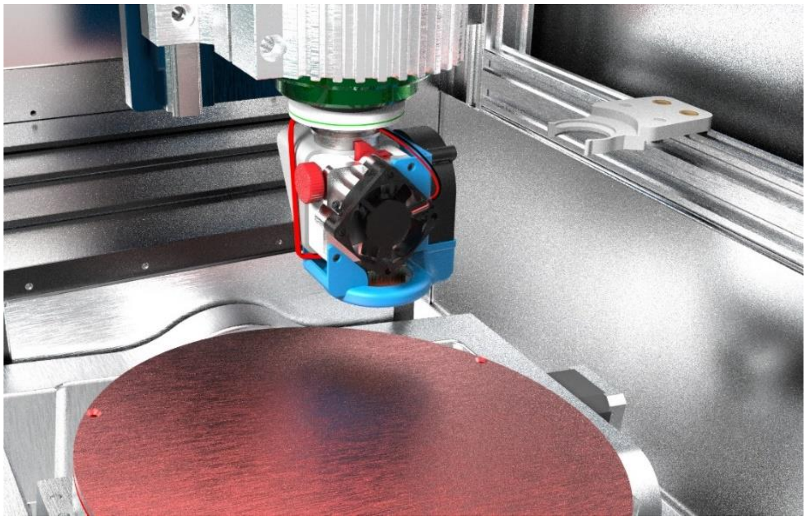

Figure 6: 5-axis Hybrid Machine Tool with automatic tool changing machine

4.1 Cost analysis

Production cost analysis plays a crucial role for optimal product design. Reducing costs is one of the main goals in product design. CNC machining remains one of the most cost effective production methods to date, when high quality parts are needed, despite advances in technologies such as 3D printing [128]. The cost of production in CNC varies depending on the complexity of the machined parts. After designing a product, an indicative total cost of the product can be calculated. Cost analysis includes material and manufacturing costs.

Table 3: Cost analysis of the mechanism

	Parts	Producton Cost per hour (€/h)	Cost/Unit (€)	Quantity	Total Cost (€)
1	Nozzle	Commercially available	0.80	1	0.80
2	Heating Block		0.75	1	0.75
3	Heat Break		2.30	1	2.30
4	Cooling Fan		1.00	1	1.00
5	Radial Cooling Fan		0.90	1	0.90
6	Stepper Motor Nema 14		7.50	1	7.50
7	Slip Rings Connector		52.00	1	52.00
8	Tool Holder ER16		16.00	1	16.00
9	Ceramic cartridge heater		0.85	1	0.85
10	Filament Drive Gear		16.00	1	16.00
11	Ball bearing (W 627/3-2Z)		0.50	4	2.00
12	Idler Level	0.4	0.20	1	0.2
13	Motor Drive Gear		0.07	1	0.07
14	Cooler Fan Dust		2.00	1	2
15	Thumb Screw		0.20	1	0.20
16	Drive Gear Extuder		0.17	1	0.17
17	Heatsink	70	76.00	1	76
18	Cover		47.00	1	47
19	Frame		82.00	1	82
				Total	370.74

Polycarbonate filament was used for the 3D printed parts. They were 3D printed with a standard filament flow through a 0.4 mm nozzle, a layer thickness of 0.2 mm together, leading to a standard 3D printing cost of about 0.40 € per hour. More specifically, the cost of filament per hour is 0.30€ a typical electricity consumption (depending on the type of printer) costs about 0.10€ per hour ([50],[51]).

The cost of CNC machine is about 70 € per hour and varies depending on the complexity of the piece. The cost of machining parts in CNC milling machines is the total cost of the raw material, the cost of mounting and programming complexity (3-axis or 5-axis), the machining hours required to complete the components and finally the electricity that will be consumed during procedure.

5. Conclusions

In recent years, manufacturers of CNC machine tools and 3D printers have developed hybrid multi-axis machine tools for producing complex geometry components, which must be durable and accurate to minimize processing time, material waste, and resource engagement. The application of hybrid manufacturing processes has proven to be quite effective in the production of commercially ready components that require no or minimal post-processing. The high cost of acquisition and production of hybrid machine tools is not always in line with daily industrial or craft practice of producing small batches of limited cost pieces from non-metallic materials.

In that direction, this article presents the design and manufacturing of a polymer material extrusion 3D printing mechanism, ready to connect and operate with the ATC system of a CNC milling machine, for hybrid manufacturing of non-metallic materials. In a manual nozzle printer, to replace the extrusion mechanism, the user needs tools to disassemble the unit. The process of manually disassembling the unit is inefficient and time consuming, as the operator must faithfully follow each step of the printer maintenance manual. The development of this system was based on the creation of a new material extruder system for 3D printing and its adaptation to standard tool holders that are commercially available, in order to make the system more convenient and low cost. Finally, the development of the mechanism and its connection method can be applied to other 3D printing technologies, eg. Inkjet 3D Printing, Powder Bed Fusion, thus creating the prospect of creating hybrid machine tools with multiple processing heads.

References

[1] T. D. Ngo, A. Kashani, G. Imbalzano, K. T. Q. Nguyen, and D. Hui, "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges," *Composites Part B: Engineering*, vol. 143. Elsevier Ltd, pp. 172–196, Jun. 15, 2018, doi: 10.1016/j.compositesb.2018.02.012.

[2] G. M. Martinov, A. I. Obuhov, L. I. Martinova, and A. S. Grigoriev, "An approach to building specialized CNC systems for non-traditional processes," in *Procedia CIRP*, 2014, vol. 14, pp. 511–516, doi: 10.1016/j.procir.2014.03.049.

[3] E. D. Weflen, M. C. Frank, and P. Collins, "A hybrid additive and subtractive manufacturing approach for multi-material components," 2020.

[4] P. J. G. Nieto, E. García-Gonzalo, C. O. Galán, and A. B. Sánchez, "Hybrid ABC optimized MARS-based modeling of the milling tool wear from milling run experimental data," *Materials (Basel).*, vol. 9, no. 2, 2016, doi: 10.3390/ma9020082.

[5] M. Müller and E. Wings, "An Architecture for Hybrid Manufacturing Combining 3D Printing and CNC Machining," *Int. J. Manuf. Eng.*, vol. 2016, pp. 1–12, Oct. 2016, doi: 10.1155/2016/8609108.

[6] A. N. M. Amanullah, Murshiduzzaman, T. Saleh, and R. Khan, "Design and Development of a Hybrid Machine Combining Rapid Prototyping and CNC Milling Operation," *Procedia Eng.*, vol. 184, pp. 163–170, 2017, doi: 10.1016/j.proeng.2017.04.081.

[7] W. Grzesik, "Hybrid additive and subtractive manufacturing processes and systems: A review," *J. Mach. Eng.*, vol. 18, no. 4, pp. 5–24, 2018, doi: 10.5604/01.3001.0012.7629.

[8] J. M. Flynn, A. Shokrani, S. T. Newman, and V. Dhokia, "Hybrid additive and subtractive machine tools - Research and industrial developments," *Int. J. Mach. Tools Manuf.*, vol. 101, pp. 79–101, 2016, doi: 10.1016/j.ijmachtools.2015.11.007.

[9] "| Fabrisonic." https://fabrisonic.com/top-five-reasons-use-hybrid-additive-manufacturing-machines-vs-single-focus-special-machines-running-parallel/ (accessed Mar. 20, 2022).

[10] [Online]. Available: https://www.bcn3d.com/introduction-fff-3d-printing-technology-additive-manufacturing-basics/. BCN3D Technologies[1] BCN3D Technologies, "Introduction to Fused Filament Fabrication (FFF) 3D printing technology," pp. 1–15, 2019, "Introduction to Fused Filament Fabrication (FFF) 3D printing technology," pp. 1–15, 2019, [Online]. Available: https://www.bcn3d.com/introduction-fff-3d-printing-technology-additive-manufacturing-basics/.

[11] S. Singh, G. Singh, C. Prakash, and S. Ramakrishna, "Current status and future directions of fused filament fabrication," *J. Manuf. Process.*, vol. 55, no. December, pp. 288–306, 2020, doi: 10.1016/j.jmapro.2020.04.049.

[12] B. Brenken, E. Barocio, A. Favaloro, V. Kunc, and R. B. Pipes, "Fused filament fabrication of fiber-reinforced polymers: A review," *Addit. Manuf.*, vol. 21, pp. 1–16, 2018, doi: 10.1016/j.addma.2018.01.002.

[13] H. C. Song, N. Ray, D. Sokolov, and S. Lefebvre, "Anti-aliasing for fused filament deposition," *CAD Comput. Aided Des.*, vol. 89, pp. 25–34, 2017, doi: 10.1016/j.cad.2017.04.001.

[14] M. A. Matos, A. M. A. C. Rocha, and A. I. Pereira, "Improving additive manufacturing performance by build orientation optimization," *Int. J. Adv. Manuf. Technol.*, vol. 107, no. 5–6, pp. 1993–2005, 2020, doi: 10.1007/s00170-020-04942-6.

[15] D. Syrlybayev, B. Zharylkassyn, A. Seisekulova, M. Akhmetov, A. Perveen, and D. Talamona, "Optimisation of strength properties of FDM printed parts—A critical review," *Polymers (Basel).*, vol. 13, no. 10, 2021, doi: 10.3390/polym13101587.

[16] E. Zaneldin, W. Ahmed, A. Mansour, and A. El Hassan, "Dimensional stability of 3d printed objects made from plastic waste using fdm: Potential construction applications," *Buildings*, vol. 11, no. 11, 2021, doi: 10.3390/buildings11110516.

[17] M. Ziółkowski and T. Dyl, "Possible applications of additive manufacturing technologies in shipbuilding: A review," *Machines*, vol. 8, no. 4, pp. 1–34, 2020, doi: 10.3390/machines8040084.

[18] H. Quinlan, A. P. Technologies, A. J. Hart, D. Advanced, and P. Technologies, "Additive Manufacturing : Implications for Technological Change , Workforce Development , and the Product Lifecycle," no. November, 2020.

[19] C. U. Brown *et al.*, “The Effects of Laser Powder Bed Fusion Process Parameters on Material Hardness and Density for Nickel Alloy 625,” *NIST Adv. Manuf. Ser.*, pp. 100–119, 2018, [Online]. Available: https://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.100-19.pdf%0Ahttps://doi.org/10.6028/NIST.AMS.100-19%0Ahttps://nvlpubs.nist.gov/nistpubs/ams/NIST.AMS.100-19.pdf.

[20] J. Jones and P. Coates, “7 Families of Additive Manufacturing (ASTM F2792),” *Www.Hybridmanutech.Com*, pp. 1–2, 2015, [Online]. Available: https://www.additivemanufacturing.media/cdn/cms/7_families_print_version.pdf.

[21] M. L. Vlasea, B. Lane, F. Lopez, S. Mekhontsec, and A. Donmez, “Test Bed for Enhanced Real-Time Process Control,” *Natl. Inst. Stand. Technol.*, pp. 527–539, 2015.

[22] “Aeromet and Partners Continue Development of A20X Aluminum Alloy for 3D Printing - 3DPrint.com | The Voice of 3D Printing / Additive Manufacturing.” https://3dprint.com/210009/aeromet-partners-a20x-alloy/ (accessed Mar. 25, 2022).

[23] “Rapid Prototyping.” https://www.aeromet.co.uk/capabilities/rapid-prototyping#rapid3 (accessed Mar. 26, 2022).

[24] D. E. Mouzakis, “Advanced Technologies in Manufacturing 3D-Layered Structures for Defense and Aerospace,” *Lamination - Theory Appl.*, 2018, doi: 10.5772/intechopen.74331.

[25] DMG Mori, “All in 1: Laser Deposition Welding & Milling -additive Manufacturing in Milling quality,” pp. 1–12, 2014, [Online]. Available: http://us.dmgmori.com/products/lasertec/lasertec-additivemanufacturing/lasertec-65-3d#Intro.

[26] T. Right, “Pl0Us-Additive-Manufacturing-Pdf-Data.Pdf,” [Online]. Available: https://en.dmgmori.com/products/machines/additive-manufacturing/powder-nozzle/lasertec-65-ded-hybrid%0Ahttps://en.dmgmori.com/resource/blob/71066/db7d4d589d66c2838c9570d4eee3ac03/pl0uk-additive-manufacturing-pdf-data.pdf.

[27] A. Elser, M. Königs, A. Verl, and M. Servos, “On achieving accuracy and efficiency in Additive Manufacturing: Requirements on a hybrid CAM system,” in *Procedia CIRP*, 2018, vol. 72, pp. 1512–1517, doi: 10.1016/j.procir.2018.03.265.

[28] K. A. Lorenz, J. B. Jones, D. I. Wimpenny, and M. R. Jackson, “A review of hybrid manufacturing,” *Proc. - 26th Annu. Int. Solid Free. Fabr. Symp. - An Addit. Manuf. Conf. SFF 2015*, pp. 96–108, 2020.

[29] I. Gibson, D. Rosen, and B. Stucker, *3D Printing, Rapid Prototyping, and Direct Digital Manufacturing*. 2015.

[30] S. Ford and M. Despeisse, “Additive manufacturing and sustainability: an exploratory study of the advantages and challenges,” *J. Clean. Prod.*, vol. 137, pp. 1573–1587, 2016, doi: 10.1016/j.jclepro.2016.04.150.

[31] T. Tunç, Ö. Özkırımlı, and E. Öztürk, “Machining strategy development in 5-axis milling operations using process models,” *Proc. 4th CIRP Int. Conf. High Perform. Cut.*, 2010, [Online]. Available: http://research.sabanciuniv.edu/15601/.

[32] M. Heino, I. Oy, and J. Vaasko, “AUTOMATIC TOOL CHANGING SYSTEM FOR MHI3D PRINTER Subject Automatic tool changing system for MHI3D printer,” 2019.

[33] P. Czyżewski, D. Marciniak, B. Nowinka, M. Borowiak, and M. Bieliński, “Influence of Extruder’s Nozzle Diameter on the Improvement of Functional Properties of 3D-Printed PLA Products,” *Polymers (Basel).*, vol. 14, no. 2, 2022, doi: 10.3390/polym14020356.

[34] J. Zhao, “Design of 3D metal FDM printing nozzle based on melt forming,” *Chem. Eng. Trans.*, vol. 59, pp. 73–78, 2017, doi: 10.3303/CET1759013.

[35] C. Li, W. Cheng, and J. Hu, “Nozzle Problem Analysis and Optimization of FDM 3D Printer,” *Proc. 2017 7th Int. Conf. Mechatronics, Comput. Educ. Informationization (MCEI 2017)*, vol. 75, no. Mcei, pp. 270–273, 2018, doi: 10.2991/mcei-17.2017.59.

[36] Y. Tlegenov, G. S. Hong, and W. F. Lu, “Nozzle condition monitoring in 3D printing,” *Robot. Comput. Integr. Manuf.*, vol. 54, no. December 2018, pp. 45–55, 2018, doi: 10.1016/j.rcim.2018.05.010.

[37] R. Ingman, “Adaption of a Heatsink To Additive Manufacturing,” p. 70, 2019.

[38] "What is a Heat Sink - Sunpower UK." https://www.sunpower-uk.com/glossary/what-is-a-heat-sink/ (accessed Mar. 21, 2022).

[39] T. Tichý, O. Šefl, P. Veselý, K. Dušek, and D. Bušek, "Mathematical modelling of temperature distribution in selected parts of fff printer during 3d printing process," *Polymers (Basel).*, vol. 13, no. 23, pp. 1–10, 2021, doi: 10.3390/polym13234213.

[40] R. Smith, C. Technologist, and W. Jordan, "THERMAL TESTING OF A 3D PRINTED NON-UNIFORM HEATSINK AGAINST STATE-OF- THE-ART FINNED GEOMETRY 6764 Airport Road," 2015.

[41] J. Yaple, D. Bhate, B. Azeredo, and P. Phelan, "Design and Additive Manufacturing of Copper Heat Sinks for Microelectronics Cooling," no. August, 2021.

[42] BCN3D, "The anatomy of an Extrusion System," pp. 1–17, 2019.

[43] T. Faculty, "Thermal analysis of a 3d printer hotend and nozzle," pp. 1368–1375.

[44] G. Gutiérrez Arias, F. Jiménez Díaz, E. Rúa Ramírez, and J. Valcarcel Guzman, "Thermal Analysis by Finite Elements of Hotends for 3D Printing by Fused Filament Fabrication," *Period. Polytech. Mech. Eng.*, vol. 65, no. 2, pp. 129–133, 2021, doi: 10.3311/ppme.16203.

[45] M. A. Hossain *et al.*, "Low-Cost 3D Printer Drawn Optical Microfibers for Smartphone Colorimetric Detection," *Biosensors*, vol. 12, no. 2, pp. 1–10, 2022, doi: 10.3390/bios12020054.

[46] D. Lawrence Berkeley National Laboratory Washington, "Improving Fan System Performance: A Sourcebook for Industry," *U.S. Dep. Energy*, p. 83, 2003.

[47] M. Briscoe and G. Aglietti, "Spacecraft Mechanisms," *Spacecr. Syst. Eng.*, pp. 520–523, 2003.

[48] "Slip ring - Wikipedia." https://en.wikipedia.org/wiki/Slip_ring (accessed Mar. 22, 2022).

[49] G. Dorsey, "Video Signals and Slip Rings," pp. 1–8.

[50] "Calculating CNC Machining Cost: Know All Factors and Tips | RapidDirect." https://www.rapiddirect.com/blog/cnc-machining-cost-calculation/ (accessed Mar. 23, 2022).

[51] "Weerg | CNC and 3D Printing Online - Instant Online Quote." https://www.weerg.com/en/global/hmpg?utm_campaign=ADW+WRD+all+keywords+Sales-Search-656+dsk+ROAS&utm_medium=ppc&utm_source=adwords&utm_term=3d printing price&hsa_mt=p&hsa_net=adwords&hsa_ad=555922099140&hsa_src=g&hsa_cam=15069524821&hsa_kw=3d printing price&hsa_grp=131875249827&hsa_tgt=kwd-11041673982&hsa_ver=3&hsa_acc=5333437716&gclid=CjwKCAjwiuuRBhBvEiwAFXKaNHMaSrZ_7sGncYcYn098oYkl3T0yspJ1wS8waMjBcS-7lEZJY7opOxoCakcQAvD_BwE (accessed Mar. 24, 2022).