MotorPrinter

www.bestelectricmachine.com
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Project Title:

MotorPrinter: Franchise/lease/sell the only Practical 3D Printer of Highly Efficient, Axial-Flux Electric Motors and Generators or Highly Efficient, High Power, High Frequency Axial-Flux Transformers With High Performance Materials, such as Amorphous or Nanocrystalline Metal Ribbon, which will democratize the manufacture and research of high performance axial flux electric machines.

Bottom Line Up Front (BLUF):

In keeping with the spirit of "*Innovating for Our Clean, Efficient, and Sustainable Energy Future*," the MotorPrinter Project goes where no project has gone before:

> "Engineer, fabricate, and *franchise/lease/sell* the only practical 3D-Printer for the rapid additive manufacture of virtually any category of the efficient axial-flux (AF) form of electric motor and generator (i.e., electric machine) or high frequency high power transformer with the highest performing materials, such as amorphous metal ribbon, to democratize and encourage the research, development, manufacture, and application of high performing axial-flux electric machines (AF-EM) for at least electric vehicles (EV)."

Story Behind The MotorPrinter Project

While presenting high performance electric machine inventions at several academic research and development venues, such as the Sensor-less Control For Electrical Drives (SLED) 2012, the Electric Ship Technologies Symposium (ESTS) 2013, the International Electric Machines and Drives Conference & Expo (IEMDC) 2013, and the IEEE Electrification and Transportation Conference (IETC) 2014, technical conversations with professional attendees suggested that the few specialty AF-EM manufacturers closely guard their proprietary AF-EM manufacturing techniques solely for the commercialization of their brand of AF-EM and as a result, custom AF-EM prototyping for academic research and development is unique, costly and time consuming. All agreed that a 3D Printer[1] for enabling the rapid manufacture of any category of AF-EM(s), but in particular the unique ability to manufacture with high performance magnetic core materials, such as amorphous ribbon, would democratize and encourage the research, development, production, and application of AF-EM(s) for at least electric vehicles (EV).

The Big Picture of The MotorPrinter

[1] http://en.wikipedia.org/wiki/3D_printing

1. In 2015, the World Economic Forum reported the need for a transformational investment of more than $7.6 trillion over the next 25 years (or $300 billion per year) to modernize, expand, and decentralize the electricity infrastructure with the report's conclusion, "*technical innovation is the enabling key for realizing the transformation*."

2. Electricity is the most convenient and efficient means of distributing energy, particularly energy converted from renewable fuels, such as wind, hydro, solar, etc. Already 20% of energy converted from *all* fuels is distributed by electricity. Global electricity consumption is expected to grow faster than the 47% growth already experienced from 2000 to 2012 with electric machines (e.g., electric generators) producing virtually all electricity consumed and electric machines (e.g., electric motors) consuming nearly 50% of all electricity produced for the industrial sector of the United States alone. Any applied efficiency improvement to electric machines would improve the overall efficiency of the entire electricity infrastructure. Virtually all electricity produced or consumed flows through an electricity distribution or micro-distribution grid. Any improvement in the distribution grid, such as the smart grid, will have dramatic impact to the electricity infrastructure. High power, high frequency transformers will be an integral component of the smart grid, which is basically conditioning grid electricity with power electronics and high frequency electromagnetics to improve the overall efficiency, cost, reliability, and compactness of electricity delivery.

3. The electric motor-generator drivetrain of the fully electric or hybrid vehicle (EV) is considered the most convenient means for improving the overall efficiency of the transportation sector, which is the largest consumer of energy. Today, many of the most advanced and highest performing vehicles (such as Rimac C Two) are either electric or hybrid electric vehicles (EV) with highly optimized electric propulsion motor or generator systems as an integrally essential component. Since automakers are predicting a dramatic decline in vehicles solely powered by internal combustion engines (ICE) with electric propulsion as the alternative, the electric motor market for electric vehicles (alone) will reach $480B by 2028. Any applied or enabling improvement of electric machines for the transportation infrastructure would be demanded. Any applied improvement of the electric motor and generator (i.e., electric machine) for the electric vehicle or for new efficiency standards for industry, such as IE3 to IE4 to IE5, would dramatically reduce our total energy and carbon footprint but more importantly, a practical manufacturing means that cost-effectively enables the efficiency improvement, such as MOTORPRINTER, is fundamental to its successful introduction and application.

Annually equating to a $Trillion market (e.g., electric vehicle traction motors $480B, industrial motors $120B, smart grid infrastructure rebuild $300B, etc.), highly efficient electric machines, highly efficient, high power, high frequency transformers (for smart grid solid state transformers, wind turbines, etc.) are integral for this transformation and the market focus of MOTORPRINTER.

Needs Solved By The MotorPrinter

1. Virtually all electric motors or generators (i.e., electric machines) are magnetic rotating electric machines with three possible form-factors, the so-called radial-flux electric machine (RF-EM), the axial-flux electric machine (AF-EM), and the transverse-flux electric machine (TF-EM). Unlike the RF-EM with the traditional cylinder (rotor) inside a cylinder (stator) arrangement (that most of us are familiar with) or the AF-EM with the less familiar side-by-side rotor and stator disk arrangement that are now predominantly applied in some EV(s), the very rare Transverse Flux Machine (TFEM) is difficult and expensive to manufacture for practical application and as a result, will not be considered. Although the Faraday Disk (or axial-flux) electric machine was developed by Faraday in 1832, the RF-EM has been universally adopted since the very beginning of electric machine application because of the limits of AF-EM manufacturing technology at the time. Ironically, theoretical considerations by Polard[2] show the AF-EM reduces copper utilization by 13-14% and reduces iron utilization by 21.5-32.5% compared to a similarly rated RF-EM but with over a century of manufacturing tooling investment and trust in the RF-EM, AF-EM manufacturing or tooling is non-existent, proprietary, or custom. As a result, the creative research, development, or commercial application of the AF-EM is comparatively non-existent except in small specialty markets where the performance virtues of the AF-EM are cost-effectively applied, such as the EV market. Because of the improved power density and efficiency, the axial flux form is expected to be used more in the future for any application.

2. There are two forms of 3D Printers, the classic 3D Printer that builds the product object by forming physical layers with the object template of each layer from the bottom up to the top of the object, which is layering in the direction of gravity, while fusing the layers together. The Laminated Object Manufacturing (LOM) 3D Printer builds the product object by forming physical layers with the object template of each layer from inside to outside of the object, which is layering perpendicular to the direction of gravity and without fusing the layers together. Because of the layering with respect to gravity, many incorrectly do not consider LOM as 3D Printing.

3. A Design News article by senior technical editor, Ms. Ann Thryft, states, "*Oak Ridge National Laboratories (ORNL) is getting into 3D printing in a major way…[by] develop[ing] technology that will 3D print an entire production model car*." [3] For good reason, today's rage is 3D Printing (or additive manufacturing) for rapid product prototyping or for production of custom solid shapes by additively fusing thin layers of plastic or metal materials to progressively take the form of the final shape with little waste by altering the properties of the plastic or metal feedstock or layering materials, which are manufactured to be specifically compatible with the 3D Printer, from its solid (fine powder) to a localized liquid (by laser) at the focused layered

[2] Zahra Nasiri-Gheidari, Hamid Lesani,"A Survey on Axial Flux Induction Motors," PRZEGLAD ELEKTROTECHNICZNY (Electrical Review), ISSN 0033-2097, R.88 NR 2/2012.

[3] Ann R. Thryft, Senior Technical Editor, Materials & Assembly, Design News, "3D-Printing an Entire Car & a Bigger, Faster Commercial 3D Printer," 3/14/2014

boundary of the shape and then back to solid by cooling during layering process. The expensive layering materials used are preprocessed to be compatible with the 3D Printer mechanism and not with the product being manufactured. Although much less waste than a subtractive manufacturing process, such as bulk cutting the final shape from a billet of material, the 3D Printer waste is not re-usable and as a result, must be collected and properly disposed of or sent to a special reprocessing facility.[4] So, the best state-of-art 3D Printer is *not suitable for manufacturing the magnetic steel core of electric machines*, which always requires at least the additive stacking of thin insulated laminations of "pre-processed" steel ribbon (i.e., electrical steel) with special but delicate electromagnetic properties that cannot be altered during the manufacturing process without losing the original coveted performance properties, such as by the conversion from solid to liquid and back to solid. For instance, amorphous metal ribbon, which was discovered more than 50 years ago but still shows the best electromagnetic performance, requires a specialize manufacturing process of super cooling molten metal (e.g., > 1 Million degrees per second), which is not practical with 3D Printer methods. Although the ORNL 3D Printer may one day manufacture the entire conventional vehicle including the internal combustion engine and drivetrain as suggested, the ORNL 3D Printer cannot manufacture the entire electric or hybrid vehicle (EV) of the future, which includes an electric machine, without MotorPrinter.

4. The conventional laminated electrical steel core of any electric motor or generator (i.e., electric machine) shares 15% of the total energy loss of the electric machine. By simply using better performing magnetic core materials, such as readily available amorphous metal ribbon, core loss could be reduced by a staggering 80% over conventional electrical steel laminations with a proportional reduction in adverse byproducts, such as greenhouse gas. Amorphous metal ribbon shows significantly higher electrical resistance than all other available materials for significantly lower core loss (and high efficiency). Amorphous metal ribbon shows significantly higher magnetic permeability at higher power levels than all other available materials, such as electrical steels or soft magnetic materials, which significantly reduces winding magnetizing MMF (e.g., winding size and loss) or PM coercivity and thickness (e.g., Rare Earth permanent magnet size and material amount), winding loss, and smaller core size. Amorphous metal ribbon shows significantly higher resistance to eddy currents and core loss than all other available materials while supporting high power, high flux density, high frequency applications. Amorphous metal ribbon shows higher mechanical strength than soft magnetic materials, which reduces additional frame structures. But the same enhancing properties that make the magnetic core material electromagnetically efficient, also make the material extremely thin and hard and as a result, too difficult to manufacture into an electric machine core without handling difficulties, damage to the electromagnetic performance properties of the material, or rapidly wearing the tooling. Since high performance core materials have been available for decades, it is not the availability of high-performance core materials but instead, it is the lack of a practical *enabling means* to cost-effectively manufacture electric machines with high performance core materials.

[4] "Automated Metal Powder Recovery System for the Additive Manufacturing Industry," Jan 4, 2018

5. The classic study of electric machines begins with the study of AC Transformers (e.g., electric machines are symmetrical (dual ported) or asymmetrical (permanent magnet, reluctance, squirrel cage induction, etc.) AC transformers). Improving the delivery, reliability, and cost of the AC Transformer, such as the smart or solid-state transformer (SST), would have comparable impact to the electricity infrastructure as improving electric machines. Solid State or Smart Transformers require high frequency and power operation and accordingly, these transformers need a performing core material that supports high power and high frequency, which is amorphous or nanocrystalline metal ribbon.

Best Electric Machine (BEM) considers the following highly important for enabling efficient electric machines and efficient, high power, high frequency transformers:

- Novel manufacturing tools, such as 3D Printers, for the rapid manufacture of efficient electric machines and high power, high frequency transformers, particularly tools that universally manufacture high power electric machines and transformers *with the highest electromagnetic performing materials, which to date, can only be provided by specialized process manufacturing at the molecular level, such as amorphous metal ribbon*.
- The axial flux form of electric machine has been shown to reduce the amount of materials while improving performance, such as higher torque density, adjustable air-gap, and efficiency, when compared to the more common radial-flux form. Already, the axial flux form is dominant for the electric vehicle traction motor market. Belonging to the same electromagnetic family, electromagnetic transformers should show the similar results, particularly if considering SYNCHRO-SYM for the electric machine market or BMSCC for the smart grid market;
- Amorphous or Nanocrystalline metal ribbon can reduce core loss by 80%. Electric machines additively manufactured with amorphous metal ribbon, as only provided by MOTORPRINTER, more easily meet the mandated IE4 and IE5 efficiency standards, which is a formidable challenge even with today's technology.

To date, there is no known implementation of competitive technology, such as 3D Printing, for enabling the practical manufacture of highly efficient amorphous metal axial flux electric machines or efficient, amorphous metal high power, high frequency transformers, which BEM considers highly important for the electricity infrastructure. Because even labor-intensive manufacturing is compromised by the mechanical properties of amorphous metal, low cost, off-shore manufacturing is not a solution. Besides, Demographic 2050 Destiny suggest even Communist China will soon confront a serious shortage of qualified labor, which will force a "new chapter in the history of globalization where automation is king and closeness to market is crucial." Due to the electric machine structure of diverse, highly pre-processed materials, 3D Printing of electric machines is no easy feat. Two funded programs to develop a practical 3D Printer of electric machines have yet to materialize, such as Persimmon Technologies (recently acquired by Sumitomo Heavy Industries) originally completed a $14M series B with

ABB Ventures in 2014, which was originally motivated by an SBIR Phase II, and United Technology Research Center was awarded a $2.7M ARPA-E contract in 2013.

Consider the following article:

"While radial induction motor design has dominated the motor industry for many years, recently a number of alternative technologies and motor geometric configurations have entered the market or have at least been proposed. These innovations open up the possibility of developing motor configurations that are particularly suited to using amorphous metals. One particularly interesting design area is in the use of axial motor configurations. An axial motor stator can be wound around a mandrel and built up in layers. One interesting patent in this area is U.S. 8,505,351, where an axial motor stator is constructed in a rolled-up assembly. While such manufacturing methods are not yet commercially available, work on such schemes is progressing."

The MotorPrinter Solution

1. The MotorPrinter method was conceived and patented as a vertically enabling manufacturing tool of SYNCHRO-SYM Technologies. As a patented method, any end result using the method is protected, such as electric machines or high frequency transformers manufactured by the MotorPrinter method. Best Electric Machine (BEM) leveraged the patent of MotorPrinter. Conveniently, MotorPrinter will similarly democratize the manufacture and research of any category of high performance axial-flux electric machine (AF-EM), such as internal and surface PM electric machines, induction electric machines, reluctance electric machines, or high frequency high power transformer (HF-HPT) cores.

2. MotorPrinter, is the *only* practical and universal 3D Printer Method that completely builds a precision AF-EM or HF-HPT core from optimally premanufactured materials, such as at least ultrathin high performance electrical steel or amorphous metal ribbon, with the precision placement of customizable slot shapes and channels for place-holders for electric machine windings, permanent magnets, saliencies, or thermal management, and with a precision flat air-gap surface without secondary operations; but also, MotorPrinter directly builds the accommodating integral frame with bearing bezel assembly from low cost structural stock, such as steel, aluminum or composite bar stock, instead of traditionally assembling from a large inventory of pre-manufactured precision castings. MotorPrinter has virtually no tooling consumables and shows a significant reduction of cutting waste compared to traditional subtractive manufacturing methods of electric machines. The materials used, such as amorphous ribbon, are specially preprocessed for application performance and not for compatibility with MotorPrinter; and as a result, the waste needs no special reprocessing or poses environmental consequence.[5] MotorPrinter is a cost-effective, self-contained, environmental friendly, non-smokestack, household power, stackable, hybrid 3D Printer with a small footprint that fits inside a standard

[5] "Automated Metal Powder Recovery System for the Additive Manufacturing Industry," Jan 4, 2018

shipping container for self-contained portability but is capable of building several hundred horsepower rated AF-EM(s). MotorPrinter is stackable for incremental increases of production.

3. By the formulation, analysis, coordination, and direction efforts of BEM, the patented MotorPrinter method of manipulating the cutting of versatile shapes into single layers of preprocessed electrical steel ribbon (e.g., amorphous or nanocrystalline ribbon) was empirically shown and proven in cooperation with several fiber laser cutter companies, such as IPG Photonics, Oxford, MA, and an amorphous metal foundry, such as Metglas, to successfully mitigate the structural deformation and damaging effects of heat stress on the delicate properties of high performance core materials or tooling that have continually prevented their introduction into electric machines.

4. 3D Printing of electric motors and generators (i.e., electric machines) or HP-HFTs is incredibly difficult because of the robust frame and materials that must dynamically support high magnetic and mechanical forces and because of the diverse electromagnetic and electromechanical properties of the materials, such as insulated magnetic wire, laminated electrical steels, structural steels, bearings, etc., all of which lose their delicate properties when reformulated by the 3D Printer process. Seemingly, only two other companies have attempted to 3D Print electric machines, ARPA-E awarded a $2.7M contract to United Technologies Research Center (UTRC) in February of 2013 and ABB Technology Ventures pumped $14M into Persimmon. UTRC original intentions were to produce electric machines from the ground up by sputtering, which quickly became unrealizable after learning the nature of electric machine structure and material composition. Persimmon was more creative by developing an oxidizing method of insulating sputtered metal droplets into a soft magnetic composite (SMC) but like all SMC materials, the encompassing oxide layer shows very low magnetic permeability or structural strength. Because of recent lack of ongoing information, these companies seem to have failed, which was calculated risk in accordance with the original expectations (hence government funding of basic research) of 3D Printing electric machines. In contrast, MOTORPRINTER simplifies the layering construction to be specific to axial flux electric machine forms, which have been shown to be the most efficient, and to be compatible with preprocessed materials with the best structural and magnetic properties for electric machines instead for MotorPrinter.

5. Although MotorPrinter additively manufactures axial-flux electric machines (AF-EM) and high power, high frequency transformers with high performance material, such as amorphous metal, it would have limited purpose without a programmable and scalable manufacturing means for high volume production. The production speed of MotorPrinter is mostly dependent on the cutting placement speed, power, and cost of the fiber laser cutter with cutting speed of over 500 inches/sec empirically demonstrated, which reasonably calculates to an annual production rate of many thousands of AF-EM within the same small MotorPrinter footprint of a standard shipping container (or MotorPrinter POD). Self-contained and portable, MotorPrinter PODs are automatic and safe with video monitoring instead of manual functions, low

power (household) for portability, and stackable for incremental increases in production rate. Although initial intention is to manufacture the most difficult electric machine assembly, which is the high-performance AF-EM cores with integral frame and bearing assembly, the POD evolution would eventually automatically output a completely wound and assembled AF-EM product or high power, high frequency transformer with a convenient outside-to-inside winding approach (e.g., axial flux versus radial flux form). In addition, the customer can remotely download from the cloud, such as from the BEM library, predefined specifications, such as slot form, or remotely control just-in-time manufacturing. As a self-contained, low power, portable, and stackable manufacturing pod (e.g., shipping container), only MOTORPRINTER will (is expected) democratize the manufacture and research of any category of high performance, axial air-gap flux electric machines (EM), such as synchronous field-wound or permanent magnet EM, induction or asynchronous EM, reluctance EM, or SYNCHROSYM, and high power, high frequency transformers, which are expected to enable the future of the smart grid.

6. The portable footprint and low electrical power requirements of MOTORPRINTER will accommodate any electric machine manufacturing installation, such as manufacturing at small business facilities or academia's parking lots for proprietary customer research and development, or open fields with low power access, etc.

7. A computer aided design (CAD) tool, called BEM-CAD, has been developed and will be available for designing axial flux electric machines and for manufacture with MOTORPRINTER, including frame and thermo considerations.

8. Together, the BEM-CAD controlled MOTORPRINTER method provides a novel, superior thermal management method.

9. The amorphous or nanocrystalline metal ribbon axial flux core of both the PDF-HFT and electric machine as provided by the BEM-CAD controlled MOTORPRINTER method keeps the magnetic flux within the ultra-high permeability, resistivity, and flux density solid metal ribbon with only the air-gap of the electric machine as the path of low permeability, which reduces MMF (product of current and winding turns) and loss. In contrast, the axial-flux (or radial flux) core of rotating transformers (for wireless propagation of power) and electric motors have the magnetic path cross the separating air-gap of the lamination, which reduces permeability and increase MMF. Even soft magnetic composites, such as powdered metal or ferrite have microscopic insulation around the material particles that reduce permeability (by effectively increase air-gap) and lower flux saturation limits.

10. By 3D Printing axial flux cores of high-performance materials, such as thin amorphous metal ribbon, with integral frame and bearing assembly, MOTORPRINTER is an essential enabling technology for the following:
    - The world's only practical Smart grid solid-state transformers (SST) that always include an integral HP-HFT and without a DC Link Stage for smart grid phase shifting, frequency changing and synchronization, power conditioning, etc;

- The world's only practical brushless (and synchronous) wound-rotor doubly fed electric machine system, called SYNCHRO-SYM, which must include a Position-Dependent Flux High Frequency Transformer (PDF-HFT) for Brushless Real Time Emulation Control (BRTEC) to show half the cost, half the size, and half the electrical loss of any other electric machine category, including high performance permanent magnet electric motor systems;
- Practical high performance electric machines that meet IE4 and IE5 efficiency standards by incorporating high performance core material, such as amorphous metal ribbon.

The Simple MotorPrinter Functional Operation

As shown in the rudimentary concept drawing of Figure 1, the patented MotorPrinter concept of operation (CONOPS) is simple and straight forward requiring only engineering and fabrication to completion. Two rotary tables provide the "supply bobbin" and the "finish spooler." As the spool of raw amorphous ribbon is unwrapped from the supply bobbin, the ribbon passes through the commercial fiber laser cutter (FLC) with XY positioning that at least performs the customized slot cut as programmed into the self-contain computer-aided-design (CAD) packages of BEM-CAD and the turn-key FLC, and then the finished ribbon is wrapped onto the finish spooler. Not shown is the electric machine bearing assembly, which is first placed on the finish spooler before wrapping begins to form the ribbon wrapping spindle, which becomes an integral part of the frame and bearing assembly of the finished core when wrapping and fusing are completed. The progressive wrapping of the cut or finished ribbon onto the finish spooler eventually forms the toroid or disk core of an AF-EM. Each fiber laser slot cut is initiated by sensing the predefined map of slot channels provided by a slot template, which is a "predetermined map" of slot positions that synchronously follows the rotation of the

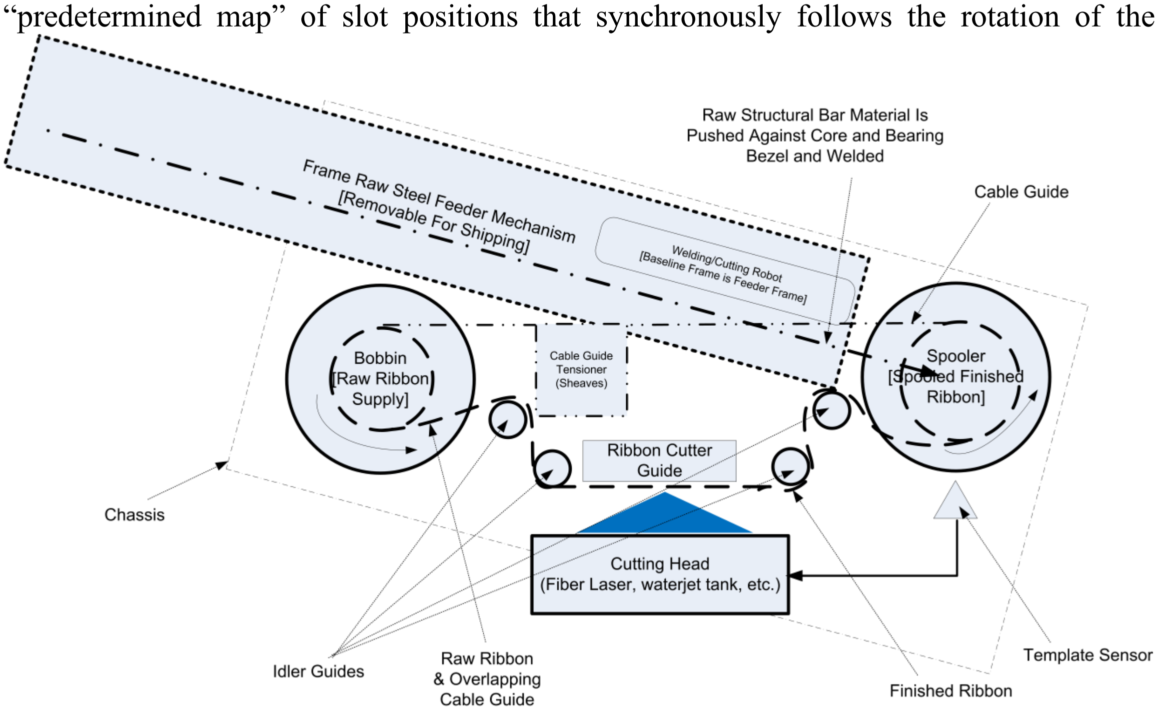

Figure 1

finish spooler, and as a result, the slots always precisely align over the previous wrapped layer of slots regardless of the unpredictable diameter of the sequential wrapping of raw ribbon with varying thicknesses. Slot cutting on an individual layer of ribbon avoids cutting stress, which damages the electromagnetic properties of the material, such as cutting slot channels on the bulk of material billet. The slot template can be running software, such as a predefined lookup table of stepper motor steps to the next slot, or hardware, such as opaque lines on a cardboard disk that are optically detected, all of which avoids the inaccuracies of dynamically calculating the position of the next slot cut from the speed of rotation and the unpredictable diameter of wrap layers with variable ribbon thickness. A "guide," such as a cable, surrounds the entire path of the ribbon from the supply bobbin to the finish spooler to at least guide the moving ribbon within the expected path. On each wrap, the ribbon assumes the shape of the flat surface of the precision flatness of the finish spooler, which is the air-gap side of the finished toroid core. After the wrapping is completed, the robotics of the "raw steel stock feeder mechanism" with a rudimentary concept shown in Figure 2 precisely places bar or channel stock (for instance) onto the back-side of the finished toroid core like spokes on a bicycle wheel with the "Welding/Cutting robot" attaching the bar or channel stock to the back-side of the toroid core with the guide cable continually holding the finish toroid in alignment to the finish spooler, which also acts as a precision alignment jig for at least the precision flat air-gap surface and frame assembly. Any imprecision of the ribbon and frame materials is neutralized by the forgiveness of jig welding, gluing, or fusing. The process is repeated until the all of the bar stock spokes are welded to the toroid core and bearing assembly for a finished toroid core with integral frame and bearing assembly and

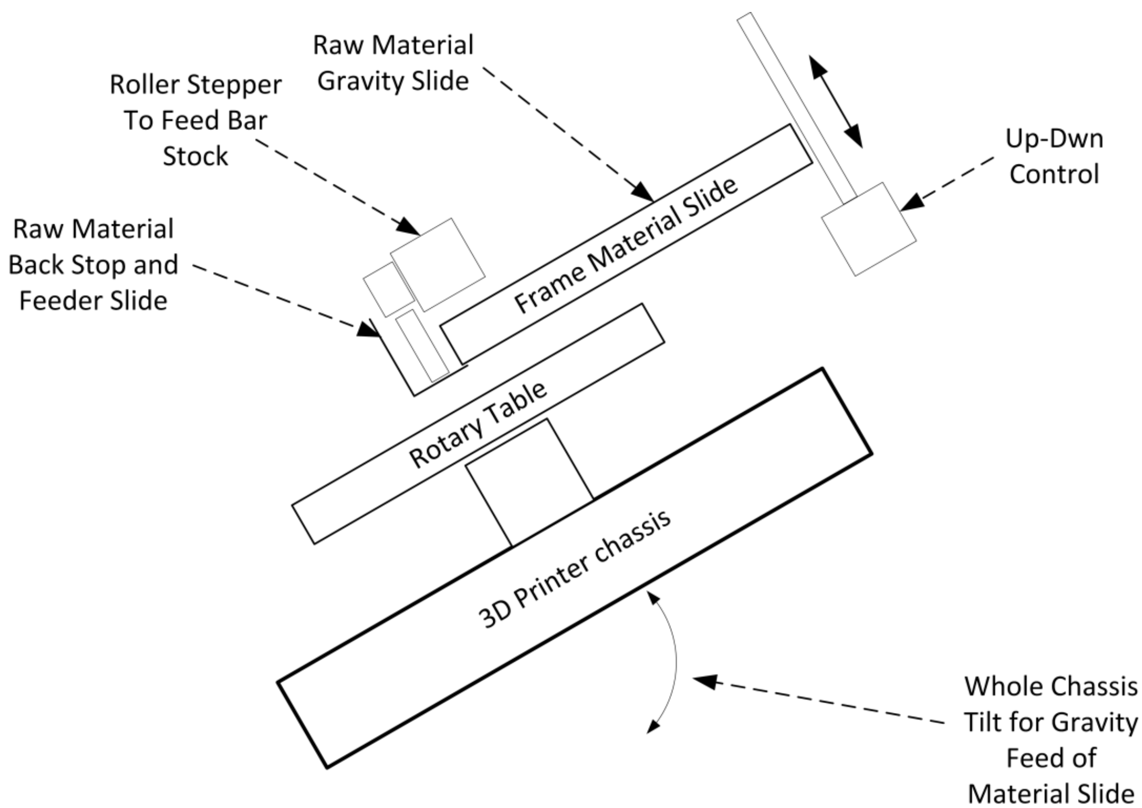

Figure 2

precision flat air-gap surface.

Different from other Laminated Object Manufacturing 3D Printers, MotorPrinter comprises at least four unique intellectual property claimed aspects: 1) the slot template means for initiating the remote slot cutting on a single wrap layer of ribbon to relieve heat stress on the material while precisely aligning the slots on the toroid without dynamic calculations; 2) the air-gap side of the ribbon progressively assumes the precision flat surface of the finish spooler on each wrap without follow-up machine processes, such as Blanchard grinding, and 3) a robust frame and bearing bezel assembly; 4) computer aided design tool (i.e., BEM-CAD) specific for Motorprinter; and 5) the cable guide for actively guiding the ribbon path.

Why 3D Print axial-flux electric machine and high frequency transformer cores with integral frame as *only* provided by MotorPrinter?

- MotorPrinter is the only practical additive means of manufacturing electric machine (including high power high frequency transformer) cores with amorphous or nano-crystalline metal ribbon, which is the strongest, highest performing electromagnetic material available.
- MotorPrinter manufactures any family of axial flux electric machine, such as synchronous, asynchronous, reluctance electric motors/generators and transformers. The axial flux electric machine has been shown to use the least amount of copper and electrical steel but provides the highest torque with the most efficiency. [6,7]
- MotorPrinter accommodates electric machine prototyping or high volume production environments.
- MotorPrinter dynamically cuts any shape of slot (and slot channels), where the windings, permanent magnets, or salient poles reside, with precision slot overlap alignment between ribbon layers, regardless of the varying tolerance thickness or the exceptional material hardness, such as amorphous metal ribbon, and without dynamic slot position calculation that is based on wrap diameter.
- MotorPrinter inputs raw input materials that are readily available from off-the-shelf material stock, such as amorphous metal ribbon, which are already optimized at the atomic level (structural, heat conductive, electromagnetic, efficiency, etc.) for the highest performance possible and manufactured under the lowest cost, highest volume, and most optimized manufacturing processes available.
- MotorPrinter will globally democratize the manufacture of high performance electric machines with the highest performance materials available.

[6] A single airgap, axial-flux form factor is the classic two adjacent hockey puck form with the rotor and stator being the hockey pucks.

[7] The Advantages of axial flux over the traditional radial-flux form factor are: 1) high torque and less copper and steel and 2) easier for automated winding (equal advantage of soft magnetic composites (SMC)) by an outside-in approach to winding. Theoretical considerations by Polard [*Zahra Nasiri-Gheidari, Hamid Lesani,"A Survey on Axial Flux Induction Motors," PRZEGLAD ELEKTROTECHNICZNY (Electrical Review), ISSN 0033-2097, R.88 NR 2/2012*] show the axial-flux electric machine can reduce copper utilization by 13-14% and iron utilization by 21.5-32.5% compared to the traditional radial-flux electric machine. Furthermore, amorphous metal can reduce core loss, which is 15% of the total loss of any electric machine, by up to 80%, but show properties that make manufacturing difficult (e.g., no practical amorphous metal electric machines is available to date)

- MotorPrinter is an enabling technology for the patented Brushless Multiphase Self-Commutation Control (BMSCC) technology or Brushless Real Time Emulation Control (BRTEC). In effect as a SST, BMSCC is an enabling technology for the smart grid, such as phase shifters, frequency synchronizers and changers, power conditioners, etc., but more importantly, BMSCC is an enabling technology for the only brushless and synchronous wound-rotor doubly-fed electric machine technology available, SYNCHRO-SYM, which relies on the combination of low and high frequency magnetics with magnetic power sharing (instead of large capacitors banks) that is only practical with amorphous or nanocrystalline ribbon cores.
- MotorPrinter additively manufactures high frequency (PDF-HFT) and low frequency axial-flux SYNCHRO-SYM cores on the same frame and bearing bezel assembly.

The MotorPrinter Project Development Effort

The following illustrations show the MotorPrinter prototype, which is 50% complete. As a prototype, the design and assembly concept may change in final production. Additional trade secret items have not been conveniently shown in the drawing. What is shown demonstrates the simplicity of fabricating MotorPrinter, in contrast to the complicated research and development of other 3D Printers.

- Figure 4 illustrate the MotorPrinter concept, which is a portable manufacturing POD that comprises at least a MotorPrinter for the high volume, additive manufacture of wound axial flux cores with integral frame and bearing bezel assemblies (less the off-the-shelf bearings) for any category of axial flux electric machines and transformers with up to 1000 KW of power rating. Supplied with only household electrical power instead of industrial real-estate power, each portable POD is as small as a low cost 8’ x 8’ x 20’ shipping container with 65,000 lbs of structural integrity for incremental increases of manufacturing real estate and production by simple parallelization with vertical or horizontal stacking.
- Figure 3 shows early development of some of the prototyping components, such as linear slides and air-cylinders, welded structural steel, rotary table bearings, and electric motor drives.
- Figure 6 and Figure 5 show the overall view of the MotorPrinter, including the precision flat rotary tables and cable guide, which contours the flat air-gap surface of the electric machine (or transformer) without any core material performance damaging secondary machining processes, such as Blanchard grinding.
- Figure 7 shows the 50% completed MotorPrinter with linear slides, air cylinders, Pneumatic Guiding Cable Slack Absorber and Tensioner, Ribbon-Laser Guide Table, etc. The galvo-positioning fiber laser cutter and other automation components are not yet included.
- Figure 8 shows a portion of the air valve controller and motor controller panel.

MOTORPRINTER Progress

Development Stage	Development Stage Description Finished In Progress	Stage Completion
Step 1:	Fabricate the MotorPrinter platform (as shown)	50% Complete
Step 2:	Using real amorphous ribbon, empirically adjust, verify, and validate for the following: 1) Automatic spooling of the amorphous ribbon 2) Dynamic ribbon packing tensioning for layering density 3) Trade Secret Integration	60% Complete
Step 3:	Program Automation Control	70% Complete
Step 4:	Mount the galvo-positioning fiber laser cutter onto the laser guide head (middle of picture), which will dynamically cut the winding slots to precisely position on the previous layer of slots (one of my claims)	80% Complete
Step 5:	Validate and Verify (with amorphous metal ribbon): dynamic high speed laser cutting while dynamically aligning each layer of the slots with any shape or channel contour	90% Complete
Step 6:	Validate and Verify the Integral Frame and Bearing Assembly Mechanism	100% Complete
Step 7:	Validate and Verify the automated winding assembly[8]	Begin complementary Winding Tool Development
Step 8:	**Franchise/lease/sell Marketing**	

Without considering: 1) the simple concept description; 2) the patent vetting before issuance; 3) the empirical study in cooperation with fiber laser cutter and amorphous metal manufacturers; and 4) the concept vetting with major amorphous material manufacturers, MotorPrinter is a simple engineering and fabrication project. There are familiar examples of creative fabrication projects with comparable straight-forward simplicity to the MotorPrinter project, such as the creative custom motorcycle fabrication projects of Orange County Cycles or Jesse James Cycles reality TV series. Likewise, the MotorPrinter's creative fabrication project will leverage readily available commercial components into the design to significantly reduce non-recurring engineering (NRE), costs and schedule risks, such as components from hardware stores, hobby shops, auto parts stores, off-the-shelf laser cutting systems with self-contained turn-key XY positioning and a computer-aided-design (CAD) package, etc. To save development cost and schedule, there may be significant difference between the rudimentary concept of Figure 1, Figure 2, and the final MotorPrinter results.

[8] Until the slot deposition of insulated copper magnet wire winding is perfected, MOTORPRINTER incorporates the versatility of additive slot insertion of one winding at a time by automated winding of highly optimized off-the-shelf magnet wire.

The MotorPrinter Project Risk Assessment:

MotorPrinter will be developed using a creative fabrication project approach. Although no practical AF-EM 3D-Printer is commercially available or ever built, the risk is rated low by the following assessment:

- ✓ MotorPrinter is straight forward engineering and creative fabrication beyond technical readiness level seven (TRL 7). (see pictures)
- ✓ The actual fabrication of the MotorPrinter is simple and straight-forward with critical risk components commercially provided, such as the turn-key fiber laser cutting tool with its self-contained CAD package and XY positioning;
- ✓ With every opportunity, the simple and straight-forward MotorPrinter fabrication will leverage readily available off-the-shelf components from auto part stores, hardware stores, hobby shops, etc. to continually reduce the overall design risk and cost of custom components;
- ✓ Although the fabrication is conceptually simple, the USPTO patent process already vetted at least the technical soundness, creativeness, and uniqueness of the patented MotorPrinter by patent attorneys, engineers, and experts;
- ✓ Without reservations or concerns, only approvals were expressed when recently discussing the MotorPrinter technical concepts to technical principles, chief scientists, etc., with potential vested interest, such as electrical steel ribbon manufacturers, fiber laser cutters, etc.
- ✓ Already, a comprehensive cutting studies on amorphous material was empirically performed by BEM orchestration, coordination, and direction of several fiber laser cutter manufactureres, such as IPG Photonics, and amorphous metal manufacturers, such as Metglas, that showed the fiber laser cutter has the highest precision cutting speed, the simplest ease of use, the longest life, and the lowest cutting cost with a satisfactory cut of the amorphous ribbon material and without tooling consumables.
- ✓ An electric machine expert and industry icon, Mr. John Petro wrote, "An axial motor stator can be wound around a mandrel and built up in layers. One interesting patent in this area is U.S. 8,505,351, where an axial motor stator is constructed in a rolled-up assembly."

Notes:

- Well known, conventional radial flux electric machine manufacturing, such as lamination stamping (punching), is not compatible with ultrathin amorphous metal ribbon, which is a very hard material with special but delicate electrical and magnetic properties that are lost under conventional manufacturing.
- Amorphous metal ribbon and the single air-gap axial-flux form factor as only provided by the patented MotorPrinter may be the only *practical* means of meeting the imminent IE4 to IE5 efficiency standard for electric machines as demonstrated by the long and costly development effort of the Hitachi IE4-IE5 motor.

The MotorPrinter Franchise/lease/sell:

Not yet formulated, the franchising, leasing, or selling opportunity of MotorPrinter will leverage the best of many franchising, leasing or selling opportunities with one exception, MotorPrinter's purpose will democratize the manufacture of high performance axial flux electric motors and generators or high power high frequency electric transformers with high performance materials, such as amorphous metal ribbon, by the only 3D Printer available for electric motors and generators and high power high frequency transformers. Customers of MotorPrinter are motor rebuilders/rewinders, motor researchers, big or small motor manufacturers to provide motor/generator products, big or small electric vehicle manufacturers to provide organic manufacturing, etc. Any Motorprinter opportunity will require a non-disclosure agreement to protect at least trade secrets. Following other franchising, leasing, or selling opportunities, any franchise/lease/sell opportunity will include at least training, MotorPrinter POD, BEM-CAD, etc. BEM may also provide market product research from our extended product line, such as SYNCHRO-SYM, approved raw materials, and other, such as component assembly and test.

MOTORPRINTER PICTURE HISTORY:

Figure 4

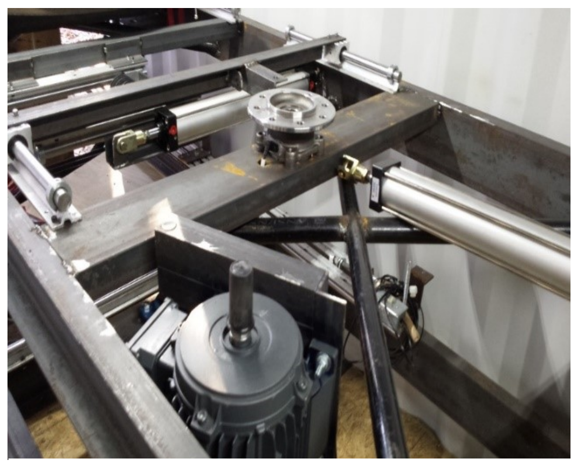

Figure 3

Figure 6

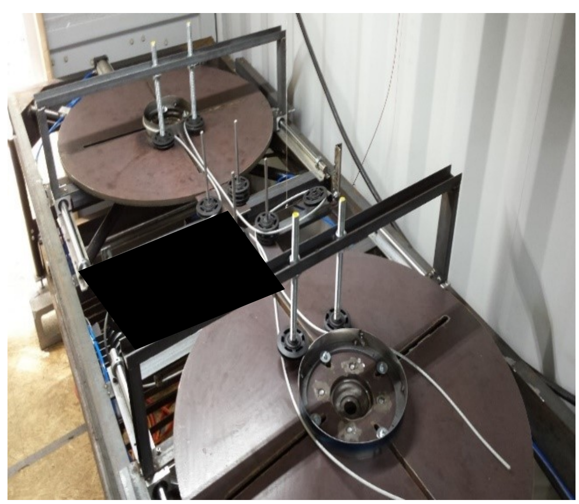

Figure 5

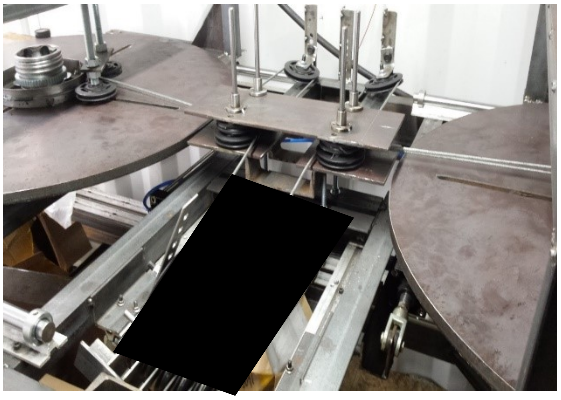

Figure 7

Figure 8